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A numerical study on circulation and volume transport in Singapore coastal waters

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Abstract

The circulation in Singapore coastal waters is driven by the variable tidal forcing of the surrounding seas, complex bathymetry, irregular coastlines, seasonal monsoons and local winds. An unstructured-grid SUNTANS model, with an average resolution of 100–200 m around Singapore, is applied to Singapore coastal waters. The model is forced at the three open boundaries, located to the west, south and east of Singapore, using tidal constituents as extracted by the OSU Tidal Prediction Software (OTPS) and Absolute Dynamic Topography (ADT) as derived from satellite imagery. The model is also forced by hourly observed wind data at 59 stations in the domain. Our calibration results show that the model accurately predicts sea surface elevations and velocities at locations throughout the model domain. Model results are used to delineate circulation patterns in waters around Singapore, and these results show significant seasonal variation. To examine the effects of different forcing terms on volume transport, a new decomposition method is proposed. It is found that: (1) ADT is the predominant factor that drives monthly mean volume transport, especially in Malacca Strait; (2) the combined effects of tides and local winds influence monthly mean volume transport, especially in Java Sea; (3) SLA affects monthly mean volume transport throughout the whole year; (4) volume transport induced by the combined effects of tides and local winds is highly correlated with tidal-induced volume flux; and (5) the residual effects, which can be attributed to the nonlinear interactions between different forcing terms, tend to reduce the total volume transport.

Keywords: Singapore coastal waters; Numerical model; Unstructured-grid; Circulation; Volume transport

1. Introduction

The Singapore coastal waters are defined as the area approximately between 103°E to 104.6°E and 0.3°N to 2°N. The three main surrounding water bodies are Malacca Strait to the west, the Java Sea to the south and the South China Sea to the east. The circulation in this region is highly complex due to its complicated bathymetry, irregular coastlines, seasonal monsoons and the differences in tidal influences (Chen et al., 2005, 2010; Hasan et al., 2012; Kurniawan et al., 2011; van Maren and Gerritsen, 2012). The tides in Singapore coastal waters are mixed, as semidiurnal tides from Indian Ocean and diurnal tides from Pacific Ocean meet at the western part of the Singapore Strait (Hasan et al., 2013; Wyrtki, 1961).

Two- and three-dimensional models have been employed to simulate water flow around Singapore. Cheong et al. (1991) and Shankar et al. (1997) modeled circulation in this region with a two-dimensional depth-integrated approach. While depth-integrated circulation models are able to predict sea surface elevations accurately, these models cannot predict the vertical distribution of velocity, temperature and salinity. Therefore, three-dimensional models are required for a realistic simulation of the flow field. In many three-dimensional circulation models of Singapore Strait (Chao et al., 1999; Chen et al., 2005, 2010; Zhang et al., 2004; Zhang, 2006; Zhang and Gin, 2000), the comparison of model-predicted results with observed data shows good agreement.

Recently, significant progress was made in numerical modeling of the Singapore coastal waters. Sensitivity analysis of the tidal representation in Singapore was carried out by Kurniawan et al. (2011), with a two-dimensional depth-averaged model on a spherical, curvilinear grid. They employed a structured approach to analyze the sensitivity of the modeled tides with an open-source tool (OpenDA), and found that Singapore coastal waters is most sensitive to tidal forcing along the open boundaries, compared to variations in depth and friction. Hasan et al. (2012) improved model performance by refining and aligning

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grids with depth contours. They set open boundaries far away from Singapore coastal waters to avoid underestimation of diurnal currents caused by an amphidromic point in the vicinity. They found that increasing the grid resolution only is not sufficient to substantially improve hydrodynamic models, considering the importance of grid alignment with depth contour. van Maren and Gerritsen (2012) further improved this regional model and showed that the diurnal tidal wave is primarily standing, with an amphidromic point close to Singapore. This clearly explains the dominantly diurnal current and semi-diurnal water level oscillations. They found that interaction of the diurnal and the semi-diurnal spring–neap cycles, compound tides, and the monsoon currents result in pronounced yearly and half-yearly cycles in spring tidal current amplitude. Hasan et al. (2013) analyzed intratidal spring–neap variations of turbulent mixing and stratification in the ebb-dominated Johor estuary with the improved model in Kurniawan et al. (2011). A remarkable asymmetry between flood and ebb tides is found with vertical profiles of salinity, flow velocity, and eddy diffusivity. The eddy diffusivity, energy dissipation rate, and the building up of stratification are very sensitive to small changes in the tidal currents. They also found that tidal straining is more important for the intratidal variation in mixing and stratification than tidal asymmetry.

Singapore Strait lies in the strategic crossroad of major shipping routes and houses one of the busiest shipping ports in the world. Economically, Singapore has experienced a rapid growth in the oil and chemical industry during the last two decades. Singapore is one of the largest oil refining centers in the world, with a crude oil processing capacity of around one million barrels per day. Water pollution has evolved into a serious issue, as a consequence of related frequent industrial and shipping activities in Singapore coastal waters. These activities may also seriously affect coastal planning and navigation in Singapore coastal waters. To better address these issues, an improved and thorough understanding of circulation and volume transport is essential. However, relatively few studies illustrate these well, especially the effects of different forcing terms on volume transport in Singapore coastal waters.

Preliminary work on volume transport in Singapore coastal waters has been conducted by earlier researchers. Chen et al. (2005) forced the Princeton Ocean Model (POM) with tides, monthly mean wind and hydrodynamic pressure gradient to perform simulations of flow in Singapore coastal waters. Estimates of volume transport in the Strait were found to fluctuate between 0.15 Sv eastward in the summer and 0.25 Sv westward in the winter monsoon seasons, with an annual mean of −0.04 Sv. They concluded that the net transport across the Singapore Strait is controlled by the pressure gradient created by monsoonal mean sea level differences, tidal range differences across the strait and the topography. Respective effects of forcing terms on volume transport are not well illustrated in this study. Chen et al. (2010) made similar conclusions by employing three-dimensional simulations of Singapore coastal waters using the Finite Volume Coastal Ocean Model (FVCOM). By decomposing the predicted currents into tidal, wind and eddy-driven components, they identified each of the components separately and their relative importance in Singapore coastal waters. They found that tidal circulation is dominant in Singapore coastal waters, and even though the wind and eddy-driven components are relatively small, they may have significant effects on the local circulation and material transport.

However, in earlier work concerning volume transport in Singapore coastal waters, MDT (Mean Dynamic Topography) forcing, which is the stationary portion of long-term residuals of tides, meteorological forcing and geostrophy, is ignored at open boundaries. ADT (Absolute Dynamic Topography) accounts for both stationary component of sea levels induced by MDT and their seasonal variations induced by SLA (Sea Level Anomaly), which represents the large-scale and long-term (seasons) monsoon effects (Twigt, 2007; van Maren and Gerritsen, 2012). In this paper, a three-dimensional hydrodynamic SUNTANS model forced by ADT, tides and local winds was applied to Singapore coastal waters to study effects of different forcing terms on volume transport. The paper is organized as follows. Section 2 describes the hydrodynamic model and the Singapore coastal model setup. Section 3 presents the model calibration. Section 4 provides the results and discussion, focusing on the circulation patterns and effects of different forcing terms on volume transport in Singapore coastal waters. Section 5 draws conclusion.

2. Methods

A three-dimensional unstructured-grid SUNTANS model (Fringer et al., 2006) is employed to simulate flow in Singapore coastal waters.

2.1. Hydrodynamic model

The governing equations are the three-dimensional, Reynolds-averaged Navier–Stokes equations under the Boussinesq approximation and hydrostatic assumption:

$$\frac{\partial u}{\partial t}+\nabla\cdot(\boldsymbol{u}u)-fv=-g\frac{\partial h}{\partial x}-g\frac{\partial r}{\partial x}+\nabla_H\cdot(\nu_H\nabla_H u)+\frac{\partial}{\partial z}\left(\nu_v\frac{\partial u}{\partial z}\right)\tag{1}$$

$$\frac{\partial v}{\partial t}+\nabla\cdot(\boldsymbol{u}v)+fu=-g\frac{\partial h}{\partial y}-g\frac{\partial r}{\partial y}+\nabla_H\cdot(\nu_H\nabla_H v)+\frac{\partial}{\partial z}\left(\nu_v\frac{\partial v}{\partial z}\right)\tag{2}$$

subject to incompressibility,

$$\nabla\cdot\boldsymbol{u}=0\tag{3}$$

where the horizontal gradient operator is $\nabla_H=\frac{\partial}{\partial x}\boldsymbol{e}_x+\frac{\partial}{\partial x}\boldsymbol{e}_y$, the free-surface height is h, the velocity vector is $\boldsymbol{u}$, and $u(x,y,z,t)$, $v(x,y,z,t)$ and $w(x,y,z,t)$ are the Cartesian velocity components in the x, y and z directions. The horizontal and vertical eddy viscosities are given by ν_H and ν_V, respectively. The vertical momentum equation is not present because $w(x,y,z,t)$ is solved using incompressibility. The baroclinic head is given by