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Research paper

Analyzing the physics of non-tidal barotropic sea level anomaly events using multi-scale numerical modelling in Singapore regional waters

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Abstract

The hydrodynamic flows in the Singapore regional waters (SRW) are the result of a complex mix of tide, seasonal and meteorological effects. The study of non-tidal effects or sea level anomalies (SLA) in this region has shown that it is possible to model some of these anomalies. The present study addresses the non-tidal barotropic water levels and currents in the Singapore region in detail. This analysis includes a multi-scale approach, and addresses amongst others hydrodynamic model grid resolution and the importance of resolving non-linear tide–surge interaction. The results show that the water level and current anomalies phenomena in a complex region like SRW can be effectively modelled using an approach combining non-tidal barotropic and multi-scale numerical modelling. A detailed investigation of the levels of non-linear tide–surge interaction is carried out by simulating SLA events in the Singapore regional waters during North-East (positive SLA) and South-West (negative SLA) monsoons based on ECMWF numerical weather forcing conditions. The results of combining both approaches suggest that the finer grid resolution improves the accuracy of water level and current anomalies simulations. Furthermore, the results also indicate that for the simulations of non-tidal barotropic flows in this area, non-linear tide–surge interaction is important and should be taken into account. Finally, the behaviour of the non-tidal barotropic flow in the region and its changes with tidal variation in the shallow region of the Singapore Strait is now much better understood. Therefore, for reliable operational forecast of sea level, the inclusion of non-linear tide–surge interaction should be required in numerical models to reproduce both tides and surges with improved accuracy in this region.

Keywords: Sea level anomalies; Singapore regional waters; Non-tidal barotropic modelling; Multi-scale approach; Tide–surge interaction

1. Introduction

The understanding of the generating mechanisms and the ability to generate forecasts of tidal and non-tidal flow phenomena (also known as sea level anomalies) and their forcing mechanisms for the highly complex Singapore regional waters are of both scientific and economic importance. A major step in their analysis and forecasting is the development of an accurate hydrodynamic model to predict the barotropic water levels and currents in the region. Relevant issues are model domain and grid resolution, sensitivity to model formulation (robustness), accuracy and predictability. Tide, a deterministic process, is typically used to assess a model's sensitivity and accuracy. Kurniawan et al. (2011a, 2011b) have previously analyzed and improved the tidal prediction in the Singapore regional waters (SRW) through a numerical modelling approach, which will also be used in the present study. The present study addresses the non-tidal barotropic water levels and currents in the Singapore region in detail. This analysis

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includes a multi-scale approach, and addresses amongst others hydrodynamic model grid resolution and the importance of resolving non-linear tide–surge interaction. We provide an explanation for the key results by evaluating against observations.

1.1. Earlier non-tidal barotropic studies

In the present paper non-tidal barotropic flow phenomena are defined as residual water levels and currents which are not caused by the tides. The hypothesis is that these residuals largely result from regional water level variations, called Sea Level Anomalies (SLA) (Gerritsen et al., 2009). Persistent basin-scale monsoon winds over the South China Sea (SCS) and Andaman Sea are assumed to be major contributing factors, creating differences in water levels that drive these residuals through the SRW.

Using early meteorological and hydrographic observations including in particular ship drift data, Wyrtki (1961) found that the surface SCS circulation follows a distinct seasonal behaviour. Since then, many studies on the seasonal circulation pattern in the SCS have pointed out that the circulation is mostly affected by the monsoon winds (e.g. Hu et al., 2000; Hu et al., 2001; Isobe and Namba, 2001; Metzger, 2003; Gan et al., 2006; Yuan et al., 2007; Liu et al., 2008). For the Singapore regional waters the recent analysis of observation data by Rao et al. (2009) has shown that the anomalies found within Singapore and Malacca Straits are not locally generated but are predominantly the result of large-spatial scale wind events during the seasonal monsoons. Rao et al. (2010) furthermore showed that there is a predominant trigger point off the coast of Vietnam for non-tidal events in the Singapore Straits during the North-East monsoon season. However no significant trigger locale was detected for the South-West monsoon.

Since the 1980's the seasonal circulation pattern in the SCS and its adjacent seas have also been investigated using numerical models. Most of these modelling studies (e.g. Shaw and Chao, 1994; Chu et al., 1999; Gerritsen et al., 2000, 2004; Chern and Wang, 2003; Gan et al., 2006; Sofian, 2007; Fang et al., 2009) have greatly improved the understanding of oceanic circulation in the SCS. Many of these studies, however, have low spatial resolution (>10–20 km), which may not be large enough for adequately resolving steep topography and the mesoscale flow field in the SCS. Though these models capture the larger-scale topographic and circulation features, they do not provide sufficient detail for modelling variations due to near-surface wind and atmospheric pressure in straits where much smaller-scale land–sea and islands effects are important, such as Singapore and Malacca Straits (Gerritsen et al., 2009). As a first step, Pang and Tkalich (2003) created a model that covered just the Singapore Straits, however, not allowing for direct dynamic interaction with the SCS.

An initial analysis by Ooi et al. (2009) supports the need for a South China Sea basin scale model to be able to properly model sea level and current anomalies in the Singapore region. They showed that application of wind and pressure forcing on their model for Singapore regional waters proper for periods with significant SLA features did not generate those events at all. On the other hand, their larger scale model for the South China Sea domain did generate these features and to good agreement with observational data for positive SLA events (Ooi et al., 2009, Fig. 3). A further study by Sisomphon (2009b) showed that the seasonal (annual and semi-annual) components in the tidal analysis of observations essentially represent wind-induced water levels. It also showed that inclusion of the inverse barometer correction is essential in representing the wind-induced water levels simulated with numerical models. Recent studies by Ooi et al. (2011) and Kurniawan et al. (2013) have focused on certain aspects of modelling these anomalies (positive or negative) through the use of a non-tidal barotropic flow model that covers the entire South China Sea basin, including an investigation of the significance of non-linear tide–surge interaction. They recommended that the simulations be repeated with a higher resolution model to properly assess the nonlinearity of tide–surge interaction in the Singapore and Malacca Straits.

1.2. Tide–surge interaction

Tide–surge interaction (Proudman, 1957; Rossiter, 1961), not only affects the surge magnitude, but may also alter the surge phase in the coastal zone (Davies and Lawrence, 1995; Jones and Davies, 1998, 2003; Horsburgh and Wilson, 2007). Following Rossiter (1961) and Horsburgh and Wilson (2007) showed the importance of phase shift as a key physical mechanism in the interaction between the tide and surge in coastal areas of the Northwest European shelf, when the surge part can (almost) equal the tidal water level and depths are only a few tidal amplitudes. The presence of a surge can then result in a higher effective depth and so a higher propagation speed of the total wave compared to tide only, which is the mechanism behind a phase shift between observed peak and tidal peak. Although the linear superposition of surges and tide has been used before for surge prediction, the non-linear effect caused by bottom friction and momentum advection cannot be ignored in coastal regions such as Singapore regional waters (Zhang et al., 2008). Following the study on the tide–surge interaction in the North Sea and River Thames by Prandle and Wolf (1978) based on statistical analysis of recorded water levels and analytical modelling, Horsburgh and Wilson (2007) confirmed the tendency for the larger sea level anomalies (SLAs) peaks to occur most often on the rising tide and both studies used numerical models to conclude that this pattern arises irrespective of the phase relationship between tide and surge in northern North Sea. Recent studies (Jones and Davies, 2007, 2008; Rego and Li, 2010; Xu et al., 2010; Idier et al., 2012; Olbert et al., 2013) further showed and quantified how tide–surge interaction can significantly modify water level elevations and currents in shallow regions. For the Singapore region, Sisomphon (2009a) and Ooi et al. (2011) concluded that the tide–surge nonlinearity is likely to be small.