Influence of MeteOcean processes on MSYM sea level predictions in the Singapore and Malacca Straits

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Abstract: The Malacca and Singapore Straits are known for the complex behaviour of their tides. These regions are under the influence of the Pacific (diurnal) and Indian (semidiurnal) tides, which are modified by local geomorphology and by the monsoon characteristics of the region. Furthermore, it is an economically important region, justifying the development of a local hydrodynamic numerical application (MSYM), which calculates, among other parameters, the sea level. A previous model validation revealed good results, in general. However, some discrepancies between observed and predicted sea levels were identified, mainly during neap tides and for specific tide gauges. This work explores the origin of these discrepancies by comparing predictions with observed data and by investigating the MeteOcean processes occurring in the straits. While these differences in the Singapore Strait are associated with monsoon occurrences, in the Malacca Strait they are related with minor accuracy in astronomical tide reproduction.

Key words: Singapore Strait, Malacca Strait, Astronomic tide, Storm surge, Monsoon.

1. INTRODUCTION

The Malacca and Singapore Straits are characterized by a complex tidal behavior, entangled with the co-oscillating nature of the tide from the Pacific and Indian Ocean, mainly in response to the geographical configuration of the area. The combination of these elements with the existence of many islands, small passages and sharply varying bottom topography, could give an overview of the complexity of the tides in the study area and the coastal waters' response to various forcing mechanisms that provide the energy and momentum to drive the coastal processes. In the past decade, numerical ocean models have been able to predict the coastal and oceanic processes with the necessary resolution to reproduce the small-scale details not captured by the observations, which has been useful for such areas as coastal engineering, oceanography, marine environment. The Malacca Strait is one of the most important shipping routes in the world and is a canal shipping route between the Indian and Pacific Oceans that connects three of the most populated countries in the world: India, Indonesia and China (Rizal *et al*., 2010). There has also been an expansion of the oil exploration activity in this region, which is likely to increase in the next few years, as new oil deposits are discovered and the oil spills might become more frequent (Camerlengo and Demmler, 1997). Therefore, the different aspects of removal and containment of oil spills under adverse weather conditions will necessarily have to undergo an accelerated expansion in the near future.

The MSYM model was created in order to be used as an operational oil spill forecast system for the Strait of Malacca. Thus, appropriate hydrodynamic and oil dispersion models are expected to be used to provide predictions of the movement, dispersion and trajectory, shore reach and impact of pollutants on the coastal area and marine structures. The solution proposed will make use of AQUASAFE server to manage the information and MOHID to compute the hydrodynamic and oil spills transport and dispersion. MOHID is an integrated water modelling software which has been used to simulate physical, chemical and ecological processes at different scales in several coastal and estuarine areas worldwide showing its ability to simulate complex features of the flows (e.g. Martins *et al*. 2001; Vaz *et al*. 2005).

The first validation work conducted for the model implemented for the Strait of Malacca reveals, in general, similar results between observed and predicted data. However, for some locations, the discrepancies between sea level observations and the model predictions are higher under important dynamic ocean and meteorological processes. It is important to understand the reasons for these inaccuracies, mainly associated with the neap tide, so that model predictions can be improved. Thus, this work aims to deeply validate the MSYM model's sea level and understand the correlation between the highest discrepancies between the predicted and observed sea level and the main dynamic processes acting over the region.

2. STUDY AREA

The Malacca Strait is a channel with complex topography, between the Malaysia Peninsula and Sumatra, which links the Indian Ocean and

Andaman Sea (North) to the South China Sea (South). It is about 980 km long and varies in width from 52 km to 445 km and water depth changes slightly from 30 m to 200 m. The connection in the South is a channel called Singapore Strait that extends for 105 km and where the water depth ranges between 30 and 120 m. It is influenced by the interactions between the Indian (mainly semidiurnal) and Pacific Oceans (mainly diurnal) with a complex tidal pattern. The entire region, bounded by the Gulf of Thailand in the north, Karimata Strait in the south, east coast of Peninsular Malaysia in the west, and break of the Sunda Shelf in the east, typically equatorial, could experience positive or negative sea level anomalies, under the strong influence of the Asian monsoon, which greatly affects their circulations: northeast (NE) monsoons, from November to March, and southeast (SW) monsoons, from May to September. These act over the South China Sea and tend to induce positive or negative sea level anomalies in the Singapore Strait (Tkalich *et al*., 2012; Choon *et al*., 2006). The pile up of water during the winter monsoon is greater than the lowering of the sea level in the summer monsoon (Azmy *et al*., 1991).

3. METHODOLOGY

The Mohid model was used in this work to compute sea level. This hydrodynamic model has been configured to be applied in the Strait of Malacca - the MSYM model. The MSYM adopts a downscaling approach using four levels of grid nesting with different dimensions and horizontal resolution (L1, L2, L3 and L4 in the Fig. 1).

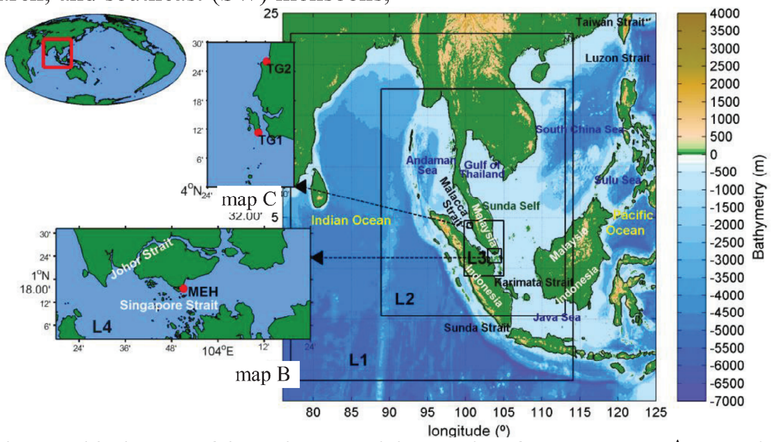

Fig. 1- Location and regional bathymetry of the study area and the nested configuration o map A YM model (map A): Level 1 to Level 4 (amplified in map B – L4). Map C contains the location of the tide gauges of the HYDEC Company ("TG1" and "TG2") and map B contains the tide gauges from the Marine Electronic Highway (MEH).

One-way nesting is used, in which the large-scale models influence the local models, but not the opposite. At this stage, all of the levels are 2D-H barotropic, using only 1 sigma layer in the vertical dimension. The first domain, in which a sea level interpolated from the FES2004 global tidal solution (Lyard *et al*., 2006) was imposed in the open boundary of Level 1, has a horizontal resolution of about 10 km. The second domain is regional and has a horizontal resolution of 5 km in which the open boundary conditions were defined by adding the inverted barometer effect to the solution of Level 1. The surface boundary condition for wind stress and atmospheric pressure is applied by using the GFS NOOA weather prediction solution. The third domain comprises the Malacca Strait, with a horizontal resolution of about 1 km. The fourth domain is local and includes the Singapore Strait, with a 200 m horizontal resolution. The open boundary conditions for levels 3 and 4 are prescribed from the upper levels, and meteorological forcing (wind and atmospheric pressure) are still being applied using the GFS solution.

Two simulations are performed during this study. The predicted sea level was forced with the astronomic and meteorological tide simulating the Singapore Strait area (L4), in the first run and the Malacca Strait (L3), in the second run. In order to validate the predicted sea level amounts, three tide gauges were considered. The simulations have a different time interval, depending on the data sources. The first time interval (24/11/2012 - 6/04/2013) corresponds to the available observed sea level provided by the Marine Electronic Highway Project (MEH) for Tanjong Pagar, in the Singapore Strait. The second time interval (5 - 19/04/2010) is related with the available observed data of the HYDEC Company for the two tide-gauges in Pangkor (TG1 and TG2). The sample interval varies with the tide gauge: 30 and 10 min, for MEH and HYDEC tide gauges, respectively. The model was spun up from rest over three days.

The analysis was divided into two main parts. First the ability of the MSYM to predict the astronomic tide was analysed, by computing and comparing the resulting amplitude and phase of the main harmonics constituents from model predictions (applying the harmonic analysis package developed by Pawlowicz et al., 2002) with observations.

In the second part, the sea level anomalies were investigated, and the origin of the discrepancies were explored and related with the MeteOcean processes occurring in the straits. Some error measures were calculated: the Root Mean Squared Error difference, the Correlation coefficient, the Relative Error. To compare the amplitude and phase of each harmonic constituent ( ), the Mean Complex Amplitude Error (1) and their Relative (2) value were computed, where h_{mod}, h_{obs}, φ_{mod} and φ_{obs} are amplitudes and phases as simulated in the model and in observations, respectively.

$$HC_i = \left\{\left[h_{mod_i}\cos(\varphi_{mod_i}) - h_{obs_i}\cos(\varphi_{obs_i})\right]^2 + \left[h_{mod_i}\sin(\varphi_{mod_i}) - h_{obs_i}\sin(\varphi_{obs_i})\right]^2\right\}^{1/2} \quad (1)$$

$$Relative\ HC_i = HC_i / h_{obs_i} \times 100 \quad (2)$$

4. RESULTS AND DISCUSSION

To evaluate the MSYM sea level predictions, data sets have been subjected to harmonic analysis separating 35 and 17 harmonics constituents, for the first and second time interval, respectively. The amplitude and phase of the main constituents were plotted the Fig. 2, for observations (blue) and predictions (red), as well as the Relative Mean Complex Amplitude Error (Relative HC, bottom), for: MEH (left), TG1 (center) and TG2 (right). The MEH results reveal slight differences between the observed and predicted amplitude and phase of the main harmonic constituents, whereas the results for TG1 and TG2 show significant discrepancies. The highest Relative HC of MEH results is 14.9% for S_2 while the TG1 and TG2 results shows Relative HC's between 13.2% (M_2 in TG2) and 218% (O_1 in TG2), considering the main harmonics M_2, S_2, K_1 and O_1. The form factor was also calculated. The results for the observations (predictions) were: 0.589 (0.567) in MEH; 0.282 (0.208) in TG1 and 0.236 (0.248) in TG2. Thus, the errors in the factor form are: 3.81% for MEH; 26.46% for TG1 and 5.38% for TG2. It should also be taken into account that MEH tide gauge is located in the Singapore Strait; TG1 is located in an estuary and TG2 on a bay. Thus, each place was associated with different coastal processes, time intervals and sample times. The time series of 15 days for HYDEC tide gauges is not enough to separate the four major constituents. The frequencies with higher amplitude of the sea level anomalies (Fig. 3) can also be related with astronomical tide frequencies that the harmonic analysis cannot separate due to the time interval.

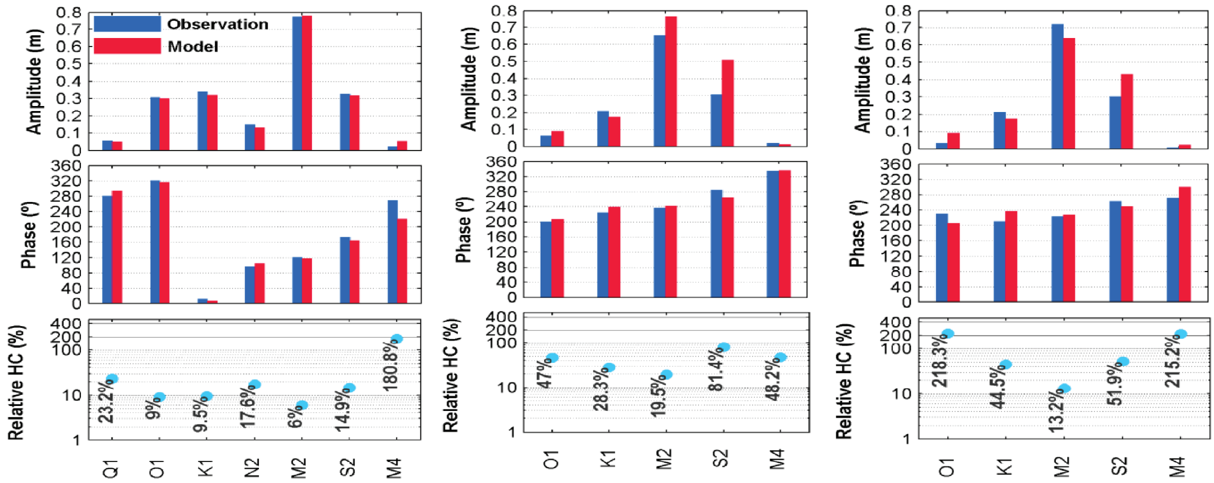

Fig. 2 – Harmonic analysis for the MEH and HYDEC tide gauges: Tanjong Pagar (right), TG1 (center) and TG2 (left). Amplitude (top), phase (center) and Relative mean complex amplitude error (Relative HC, in the bottom).

As previously described the South China Sea is a very dynamic region, with consequences in the sea level patterns and it is affected by monsoons which dominate the larger-scale sea level dynamics. The typical monsoons for the MEH tide gauge's analysis period are from NE and the higher frequencies of the sea level anomalies indicate storms. According to Tkalich *et al.* (2012), the NE monsoon climatology and extreme wind, when aligned along the longest Taiwan–Singapore axis, produce the strongest positive sea level anomalies in the MEH region. With the goal to evaluate the relationship between sea level anomalies in the MEH tide gauge and the wind speed along the aforementioned axis, the correlation coefficient between the gridded wind data (50 by 50 km from GFS) and the sea level anomalies was computed (Fig. 4). The highest correlations were found between 10-20°N and 107-113°E, so the occurrence of storm surges can be related with the meteorological conditions in this region. The sea level anomalies for the HYDEC tide-gauges (Fig. 3, center and right) are in the order of 10 – 20 cm. The typical wind speed in the Malacca Strait is not as high as that found over the South China Sea and no significant wind events happened during this second time interval.

The discrepancies in HYDEC tide gauges between the observations and prediction can be essentially associated with differences in the amplitude and phase in the major harmonics, which are strengthened during the neap tide.

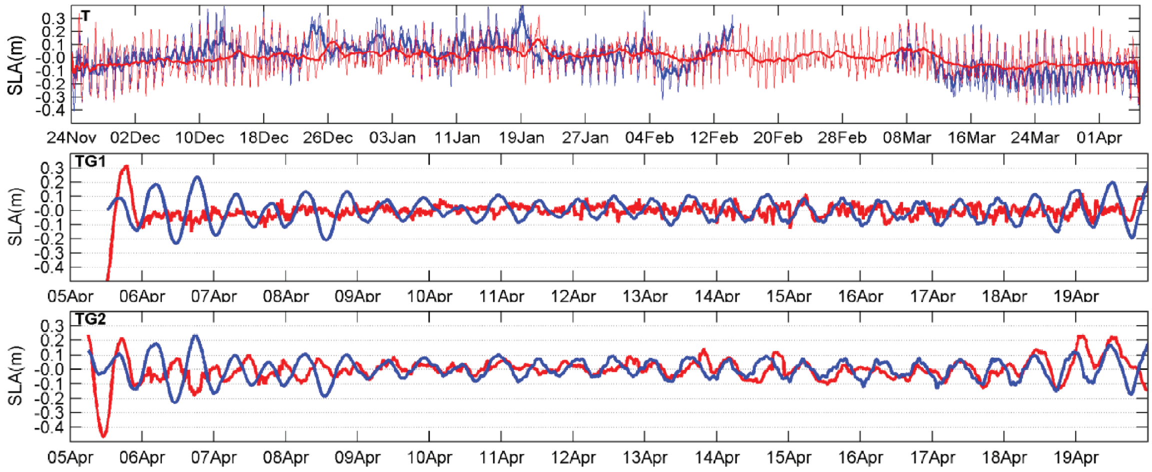

Fig. 3 – Predictions (red) and observations (blue) of sea level anomalies for MEH (top), TG1 (center) and TG2 (bottom) tide gauges

Finally, the RMSE was computed for the sea level at each tide gauge. The values vary between 12.64 cm, 18.74 cm and 22.45 cm, for MEH, TG2 and TG1, respectively, for an amplitude in spring tide of around 3 m.

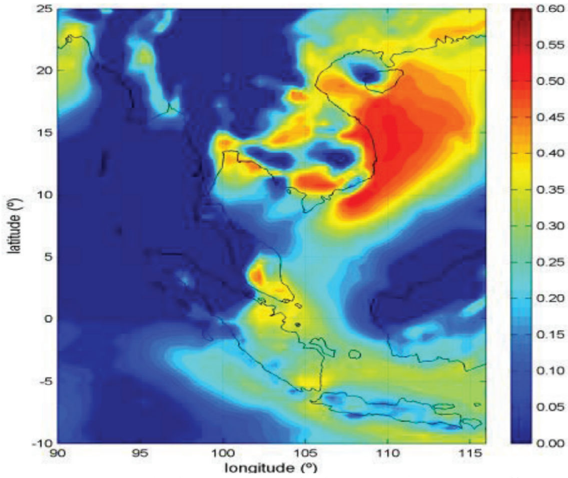

Fig. 4 - Spatial distribution of the Correlation Coefficient between the sea level anomalies in MEH tide gauge and the wind along the Taiwan-Singapore axis.

5. CONCLUSIONS

The MSYM model behaves in a different way when simulating the sea level, according to the site analysed. This is due to the region's complexity and to the local influence of several (physical and meteorological) factors. For the Singapore Strait (MEH tide gauge) a good representation of the tide was found (<4%), where the highest discrepancies between observations and predictions are usually associated with the meteorological tide due to the surface wind stress. For the Malacca Strait (HYDEC tide gauges), the highest differences are mainly related with the model's predictions for the astronomical tide (amplitude and phase).

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