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Conceptual Hydrodynamic-Thermal Mapping Modelling for Coral Reefs at South Singapore Sea

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ABSTRACT

Coral reefs are important ecosystems that not only provide shelter and breeding ground for many marine species, but can also control of carbon dioxide level in ocean and act as coastal protection mechanism. Reduction of coral reefs at Singapore coastal waters (SCW) region remains as an important study to identify the environmental impact from its busy industrial activities especially at the surrounding of Jurong Island in the south. This kind of study at SCW was often being related to issues such as turbidity, sedimentation, pollutant transport (from industry activities) effects in literatures, but seldom investigated from the thermal change aspect. In this paper, a computational model was constructed using the Delft3D hydrodynamic module to produce wave simulations on sea regions surrounding Singapore Island. The complicated semi-diurnal and diurnal tidal wave events experienced by SCW were simulated for two weeks duration and compared to the Admiralty measured data. To simulate the thermal mapping at the south Singapore coastal waters (SSCW) region, we first adapted a conversion of industrial to thermal discharge; then from the discharge affected area a thermal map was further computed to compare with the measured coral map. The outcomes show that the proposed novel thermal modelling approach has quite precisely simulated the coral map at SSCW, with the condition that the near-field thermal sources are considered (with the coverage area in the limit of 20km x 20km).

Keywords: Coral reefs; hydrodynamics; Singapore coastal waters (SCW); thermal map

1 Introduction and Motivation Statement

Singapore is regarded as one of the busiest island countries connecting the world by its shipping and haulage activities. In recent years various industrial activities have boomingly growing at Singapore and causing various environmental impacts to its surrounding waters. Thus an in-depth hydrodynamic understanding of the surrounding sea and coastal area of Singapore Island is crucial in seeking solution to the rising environmental issues. In the research of Singapore coastal waters (SCW) hydrodynamic numerical modelling, there are a numbers of difficulty that were constantly suggested in various studies [3, 19, 22, 25, 33], especially for the modelling surrounded Strait of Singapore. They include: (1) the effects diurnal to semi-diurnal tides that occur in between Singapore, Malay Peninsula and Indonesian Sumatra, (2) the huge amounts of small islands exist around Singapore (that causes difficulty in numerical meshes assignation), and (3) the effect from seasonal flow, such as Monsoon season. These difficulties couple with the grids resolution restrictions in various parts of SCW post a great challenge in the search of a numerically robust approach to reproduce its tidal currents.

During the development of hydrodynamic models for SCW, published studies using various software packages (i.e. Delft3D, MIKE, POM and FVCOM) have been intensely conducted since last two decades. Among them, most studies were done using either two-dimensional [4, 19, 27, 28] or three-dimensional models [3, 30, 31]. Among those models, the most common meshing method involved orthogonal or regular rectangular grids (as the fully unstructured grid model is computationally too demanding to apply for large-scale coastal flow application as suggested in [29]); and the boundary conditions were usually set by effective water depth. Those 2D and 3D modelling studies have proven that both local and regional models surrounded SCW can be constructed to precisely capture its tidal situation. The above-mentioned comparison from different studies also further proved that the 2D model can achieve satisfactory results and comparable accuracy with 3D model to reproduce large-scale tidal currents simulation, while giving a more efficient and hence practical tidal computational time.

Some advancements have also been proposed such as boundary-fitted [25, 32] and grid-alignment approaches [19] to obtain better accuracy in simulating the 2D tidal currents in SCW. However, the improvement in accuracy was usually restricted to only small simulated area (showed in [25, 32]) or was not obvious in tidal current and water level simulations (showed in [19]). In comparison, by refining the local mesh resolution according to the local geometry can effectively improve the water levels and tidal currents simulation as proven in various studies (refer to studies by [9, 21]), which it is also suggested to be a crucial element in the sensitivity analysis of SCW tidal simulations conducted by Kurniawan et al. [22] and Sun et al. [27].

In terms of the coral reefs mapping at SCW, it was estimated that around 60% of the SCW coral reefs have been lost in the last six decades due to its coastal development activities [7]. The common approach to study their disappearance/growth was either by investigating the factors of: 1) sedimentation and turbidity [28], 2) penetrating light-intensity due to sedimentation [12, 18], or 3) anthropogenic activities near to coral colony such as dredging, land-reclamation, industrial activities and pollutant transport effects [6, 13, 17, 20]. Comprehensive studies from different perspectives of coral reef survival (i.e. from physical and biological perspectives by Erftemeijer et al. [14], Fabricius [15], and Rogers [24], respectively) have also been conducted. The conclusion from those studies showed that even though the terrestrial sedimentation can affect the coral mapping, its effect to the shallow SCW is not obvious due to its tidal currents system and heavy mixture of marine waters that can dilute the fluvial sediment sources from their influence towards the coral reef grow [28]. Besides, the observed low sedimentation rates on coral area located at SCW (typically 5-20 mg/cm^2/day) was found to have minimal impact toward the coral reefs [12, 13], which it showed that the true reason of SCW coral map shrinking is still inconclusive. For this reason, a different coral reefs modelling study has to be conducted to determine the exact reason for coral map shrinking at SCW.

Due to the complicated condition with high diversity of reef environment in small SCW coastal area, its mapping determination has a crucial impact to unlock the true issue faced in order to save the coral reef species from further reduction [8, 28]. The reefs surrounded SCW are mainly fringing-type corals that concentrate on its coastline [5]. These types of coral reef at SCW exhibit the exact features of the tropical corals that can be threatened by coral bleaching due to: 1) the thermal stress [2, 16], and 2) the constant exposure to wet-dry condition from the mixture of high and low tides in the shallow sea [7, 26]. Therefore from the suggestions of those studies, the hydrodynamic and thermal impacts toward coral reefs are seemed to be important factors to consider in order to study the future coral map development at SCW.

In the light of the afore-mentioned studies, this work is motivated to construct a numerical approach to truly represent the coral map shrinking/growing. It starts by constructing a hydrodynamic study surrounded Singapore Island. The Delft3D hydrodynamic module used in the present study is based on the depth-averaged flow theory that coupled with wave propagation by its WAVE-FLOW module [10, 11]. Then, the industrial output derived from daily industrial waste and cooling water discharges is statistically calculated and extended into two-week simulation to model an effective thermal map surrounded south Singapore coastal waters (SSCW) region to understand the correlation of thermal effect towards the change of coral area. Two separate tests are conducted for the proposed model. First, in order to validate the hydrodynamic modelling, the wave simulation at four different parts of the SCW are compared to the Admiralty measured data for the duration of two weeks to prove the model representativeness of the actual semi-diurnal and diurnal tides at SCW. Second, the computed thermal map is compared to the coral map at SSCW. The comparisons show that the proposed thermal mapping approach can precisely simulate the area of coral reefs when the inspected area is limited to a near-field of 20km x 20km. Besides showing encouraging sign to simulate the correlated coral reef area, the proposed modelling approach also prove that thermal effect is one of the crucial factors to influence coral area grow which was constantly neglected in various SCW studies.

2 Model Setup and Description

In this study, the Delft3D model setup covers all surrounding sea regions of Singapore Island, which includes its boundaries with Johor (Malaysia) and Java Island (Indonesia). The relatively wide sea regions covered in this model allow the tidal currents computation in Singapore Strait without needing to prescribe them as boundary conditions, and hence can eliminate unnecessary pre-set conditions to influence the simulation. The grid system with bathymetry, water and land-cells, as well as land boundaries is presented in Figure 1. The bathymetry setting of the whole model is mainly adapted from Admiralty bathymetry data; and the land boundaries are adapted from the mapping using GoogleMaps. The utilised grid (under orthogonal system) varies in size to effectively represent the local flow geometry and condition. It is set to be with higher resolution (in between 20 – 150m) around Johor Strait to Tekong Island and center of Singapore Strait due to narrower geometry and existence of small islands, respectively; and in between 250 – 400m at the east and west ends of Singapore Strait. These grid resolutions are tested with three different resolution settings (course, medium and fine grid resolutions) and the most optimum medium grid resolution is chosen.

In total, this model has two open boundaries (towards the east and west of Johor) and one sub-divided open boundaries that located along the coastline of Java Islands. Besides, there are also two small open boundaries located along Johor and Tebrau Rivers at the north of the model. There are a total of 11 supporting points used for setting those boundaries, and the tide conditions of modelled region consist of the semi-diurnal tidal constituents of M2 and S2 (two high and two low tides daily) generated from the directions of the Andaman and Java Seas, and the diurnal tidal constituents of K1 and O1 (one high and one low tides daily) coming from the direction of the South China Sea (with contribution from Java Sea also).

In order to model the daily industrial waste and cooling water discharges, two point-sources are identified to be the key discharge points from the Jurong Island industrial area located at SSCW (shown at points 1 and 2 in Figure 1). The output discharge sources are calculated using the Continuous Stirred-Tank Reactor (CSTR) assumption on the existing discharge tanks at the industrial area, where their discharge and salinity output are represented as $112.5m^3/s$ and 30ppt, respectively. The ambient salinity is set to be 29.5ppt as according to the documented data. Using these inputs, the model then produces heat flow discharges toward SSCW, where the complicated SSCW tidal currents governed by the hydrodynamic model disperse them to a wider field. By averaging temperature of the considered SSCW field over every quarter-hour for two weeks duration, we then find out a full thermal map propagation of the heat flow. By comparing the modelled thermal map affected area to the actual coral map, we can then study the heat flows influence on the coral reefs grow.

3 Hydrodynamic Simulation: Model Validation

As afore-mentioned, the hydrodynamic modelling plays a crucial role to determine the accuracy of the tidal currents simulation, especially under complicated semi-diurnal and diurnal tides experienced by SCW. First to investigate the semi-diurnal to diurnal co-tide phases interaction at the Singapore Strait, the regional spatial distributed vector plots are investigated at the simulated flow region. Both amplitude and phase contributed tides, K1 and O1, as well as S2, are presented in Figures 2 and 3, respectively.

The co-tide phases plotting taken at different times during a single day at Figures 2 and 3 show the combined effects of open boundary's and bathymetry's driving tide forcing to the tidal currents. For K1 and O1 tides, they are mainly evolved from the tide forcing along the open boundary with South China Sea. Compared to K1 and O1 tides, S2 tides are stronger partly due to compressed area at the eastern part of Singapore Strait (by the existing small islands) that amplifies the vector field. The main tidal contributor of S2 tides is from Java Sea originated from the open boundary forcing, which has a stronger impact to Singapore Strait's tidal condition than Andaman Sea. This is agreed by Kurniawan et al. [22], which showed Java Sea stronger influence toward the tidal condition at Singapore Strait when compared to Andaman Sea using the tidal amplitude component study.

To determine the accuracy of the model, the simulation results are compared to the Admiralty measured gauge data in term of tide level (water level). The comparisons are conducted at four different points of the SCW model, namely at Tanjong Pagar Coast – TPC (located at south of Singapore Island), at Jurong Wharf – JW (located at south-east of Singapore Island), at Sembawang Shipyard – SS (located at the north-west of Singapore Island), and at Raffles Lighthouse – RL (located at the main-stream of Singapore Strait), which all points are presented at Figure 1. These comparisons are for the simulation period of 14 days (from 1st to 14th February 2011) to ensure multiple tidal cycles established to fully investigate the accuracy of modelled water depth against measured data. Figures 4 – 7 show the simulated water depths comparison at location points of TPC, JW, SS and RL, respectively, against the Admiralty data. The tidal ranges for all locations are approximately falling into the range of 0.1m (lowest neap tides) to 3.2m (highest spring tides). Overall, the tide wave fluctuations obtained from the model are in good agreement with the field data at all compared locations, in which the proposed model showed the averaged modelling errors of about 1.9% at TPC, 2.4% at JW, 3.0% at SS and 1.6% at RL. Some discrepancies can be observed at the peak of neap and spring tides. The most obvious neap-spring tide peak discrepancies occur at SS location which is situated at one of the narrowest channels (Strait of Johor) in the whole model, where the 2D depth-averaged approach used in the model may not reproduce the wavy tidal condition with great accuracy. However, the other tidal components including the tidal phase length and phase-shifting are estimated with good agreement and they show the representativeness of the numerically practical 2D model towards SCW.

4 Thermal Mapping for Coral Reefs Grow Study

As showing in various previous studies, the actual reason for coral reefs shrinking at the SCW (in particular, near to Jurong Island industrial area at its south) remains un-revealed. Sediment and pollutant transports as well as sediment turbidity are the key factors that were heavily investigated for SCW coral reefs disappearance in the past decades, yet their effects are found to be less conclusive toward the coral area reduction as can be seen from the summaries by Chia et al. [5], Chou [7], Chou et al. [8] and van Maren et al. [28]. Owing to those findings, the actual key reason for coral map shrinking need to be further studied for it holds the crucial role to identify the effective solution to this alarming environment issue.

With the gathered confidence from the hydrodynamic model validation at previous section, this section continues to use the established hydrodynamic model to further investigate the thermal map evolution around SSCW. A specific area at SSCW, namely the southern sea region of Jurong Island, is selected for this thermal map study as it is identified to be affected by discharges from its heavy industrial activities compared to other SCW area. The heat sources consist of both industrial waste and cooling water discharges that are diverted into the southern sea with permitted salinity level. Even though they are at the permitted level, these discharges might cause long term damage to the coral reefs environment that are sensitive towards thermal stress. Through calculation from the industrial discharges, the inputs were successfully determined to be discharge of 112.5m^3/s and salinity of 30ppt from two separate outlets close to south-east and south-west parts of Jurong Island, which same conditions are input into the model to reproduce a thermal mapping simulation (discharge points presented at points 1 and 2 in Figure 1).

The primary goal of these industrial discharge and salinity simulations is not to reproduce the absolute reality for their calculations are estimated from the limited industrial data available. Rather, the main goal is to understand conceptually their relative contribution to the thermal map around SSCW and hence to find and conclude their effect towards coral reefs. The resulting thermal maps for the investigated SSCW area comprised of the outcomes from two industrial discharge outlets is shown in Figures 8(a) – 8(d) for a daily cycle. The thermal maps series reveal that the heat flows reached majority of the investigated area by the semi-diurnal and diurnal tides combination (either by weak or strong thermal influence). Within the observed daily tidal cycle, majority of the heat sources is almost kept at the region stretching from north-east to north-west of the open sea at the south of Jurong Island, and the thermal map gets weaker towards its southern sea region. In comparison, stronger heat wave is observed to propagate north-eastward coherent to the stronger hydrodynamic boundary forcing imposed at the south-west to represent influence from Java Sea. However, the existence of numerous small islands at the south of Jurong Island effectively keeps the heat from dissipating to wider region, causing further aggravation of thermal stress towards the existing coral reefs at that region.

To investigate the impact of the heat sources propagation toward coral reefs, the resulting thermal map is statistically analysed for the period of two weeks (from 1st to 14th February 2011) to compared with existing measured coral map by ReefBase [23]. In the analysis, the thermal effect is considered using a statistical approach, where temperature of each mesh is averaged for the two-week period and if the increase of temperature reaches 0.2 ^oC or higher than ambient (29.5 ^oC), then it will be considered as having impact to the surviving coral reefs and verse visa (which this is also the corresponding level for coral bleaching at similar tropical Caribbean Sea condition around Earth Equator as showed in the summary of decadal scale studies by Baker et al. [1]). The comparisons are conducted in three separate coral reefs exist at the southern sea from Jurong Island, includes Cyrene Reefs, coral reefs near to Busing and Bukom Islands Group, and coral reefs near to Sudong Island, as presented at Figure 9. In Figure 9(a), the land-boundaries were based on the pre-land-reclamation stage (especially at and around Jurong Island), hence its boundaries showed discrepancies with the simulation land-cell boundaries, which were updated using GoogleMaps features at the particular period of the year of simulation. Overall, the comparison shows that the thermal map simulation consistently reproduce the size of the measured coral reefs at the intended near-field study area (about 20km x 20km). The measured shape of the coral map has been simulated with good corresponding, except at: (1) some small reef areas, and (2) coral reefs that are close to each other geographically. The survival of the coral reefs in those conditions might be heavier influenced by other criteria (such as sedimentation competition as well as light and salinity penetrations), hence the thermal mapping alone does not reproduce the measured data satisfactorily. Apart from that, in majority of the considered areas, the measured coral reefs are simulated well by the proposed thermal modelling approach. This outcome suggests that the thermal impact can be one of the crucial issues to determine the coral reefs shrink and grow at SCW. Besides, the proposed hydrodynamic-thermal modelling has also proven to provide a direct and representational approach to the surviving coral map.

In detailed consideration, the big reef at Cyrene Reefs [indicated by (1) in Figures 9(a) and 9(b)] has been represented well by the proposed model in terms of size and shape of the reef area; however, the two small-size reefs have not been reproduced with the same level of satisfaction. The small reef at location nearer to Jurong Island has not been detected by the model; while the shape of small reef nearer to Busing and Bukom Islands has been slightly misinterpreted. Besides the sedimentation and light/salinity factors mentioned above, the heat flows discharged from Jurong Island creates a high thermal cushion to its direct surrounding hence causing these slight misinterpretations of those small reefs. At the coral map near to Busing and Bukom Islands Group [marked as (2) at Figures 9(a) and 9(b)], the measured upper reef is simulated with good correspondence by the proposed model. The lower two reefs are reproduced as one in the simulation as their distance are too close for the proposed thermal mapping approach to accurately detect. However overall, both size and shape of the reefs are still reproduced with good correspondence to the measured data. Lastly, the reefs near to Sudong Island [indicated as (3) at Figures 9(a) and 9(b)] are simulated satisfactorily by the proposed model in both size and shape.

5 Conclusions

In this study, a numerical model has been built using the Delft3D hydrodynamic (FLOW-WAVE) module to simulate the tidal conditions around the Singapore coastal waters (SCW) region. The model was further input with the industrial discharges to simulate an effective thermal map around the south Singapore coastal waters (SSCW) area. This thermal map was then statistically converted into the affected areas that can impact the coral reefs survival. Two separate tests were conducted for the proposed modelling approach. First, the hydrodynamic modelling was validated using the Admiralty measured data from four different parts of Singapore Island. The test proved the hydrodynamic modelling accuracy with only some discrepancies of simulation results compared to the measured data at the narrower stream of Johor Strait. Second, the modelled thermal map was compared to the coral reef areas measured in Jurong Island open sea located at SSCW, and the comparison proved that the proposed thermal mapping approach has consistently represented the surviving coral map if the near-field heat source (within 20km x 20km area) was considered in the modelling. Besides proved that the thermal stress to be a crucial factor for SSCW coral reefs shrink and grow, this study also proposed a novel conceptual thermal modelling approach to simulate the coral map directly and effectively. In the future, the coupled approach using different factors, such as thermal, sedimentation and turbidity factors, should also be investigated to create a complete model for coral mapping study, in order to improve the hydro-environmental study at SCW.

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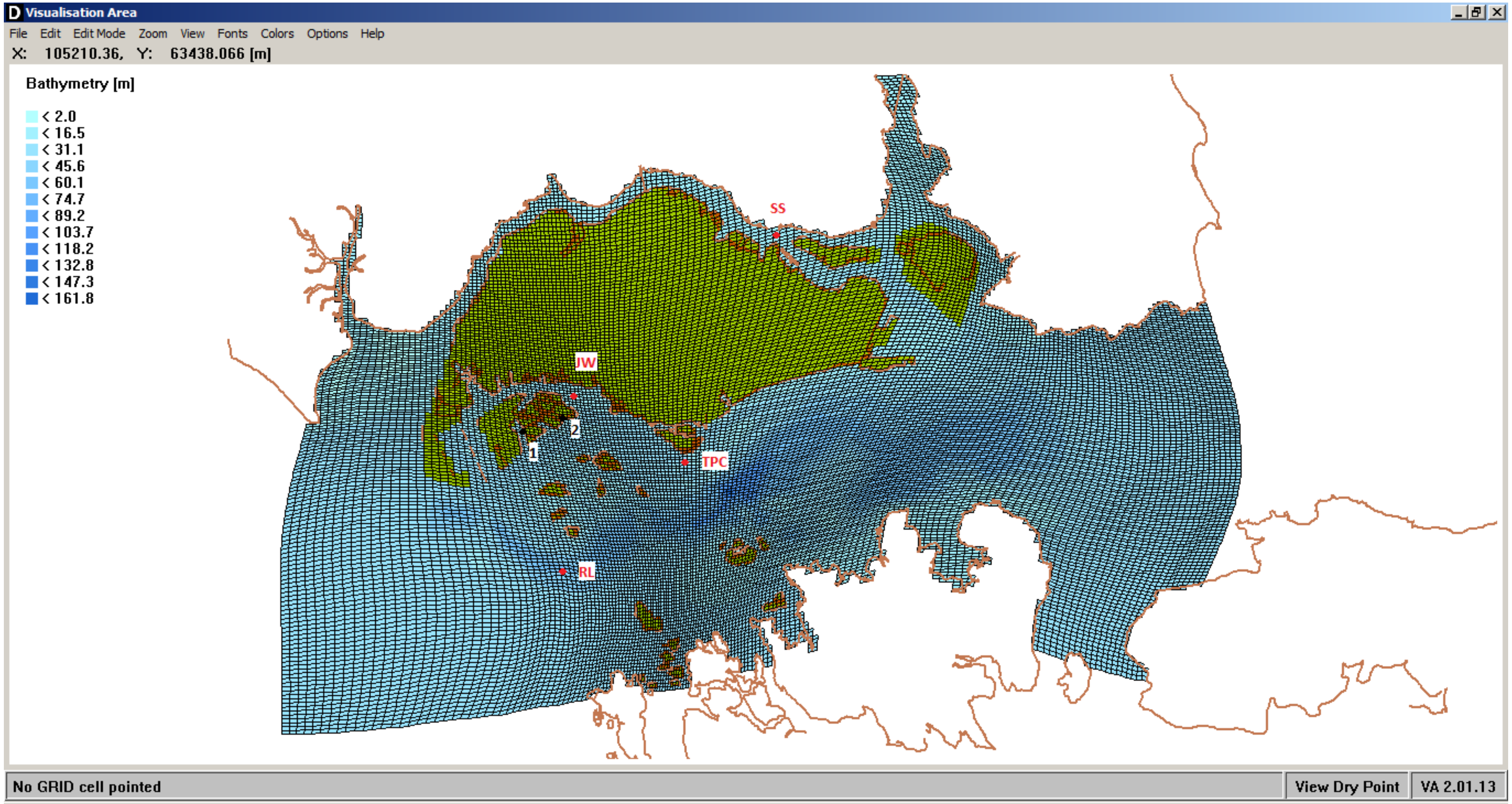

Figure 1. Deflt3D grid system for the proposed SCW model (green grids – land cells; blue grids – water cells; brown lines – land-boundaries; red points – comparison points; and dark points – heat discharge points)

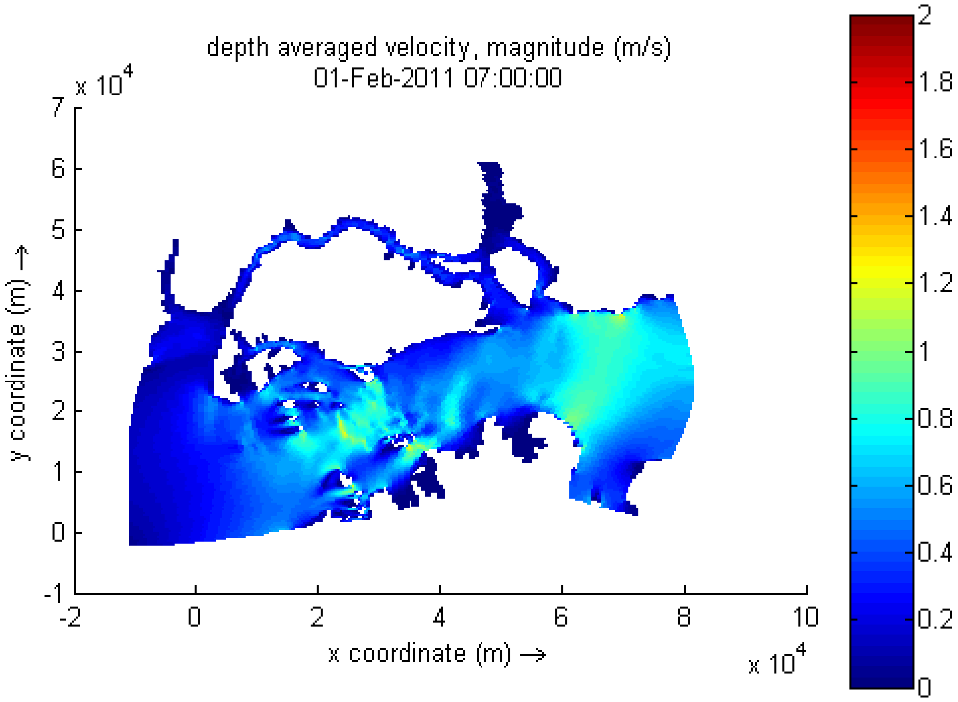

Figure 2. Spatial distribution of high K1 and O1 tides around SCW

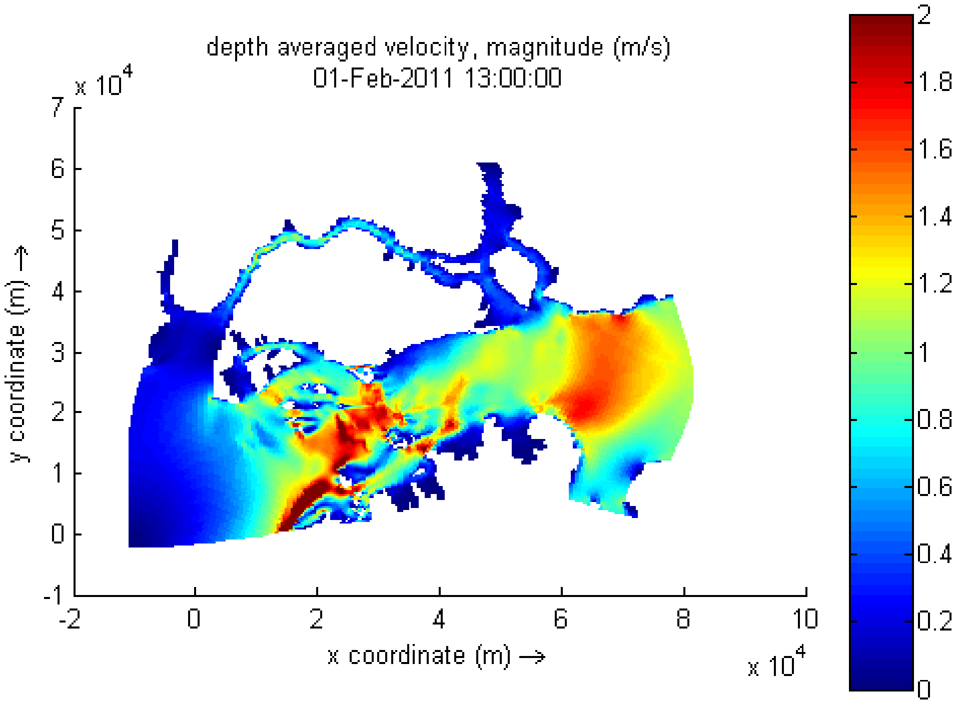

Figure 3. Spatial distribution of high S2 tides around SCW

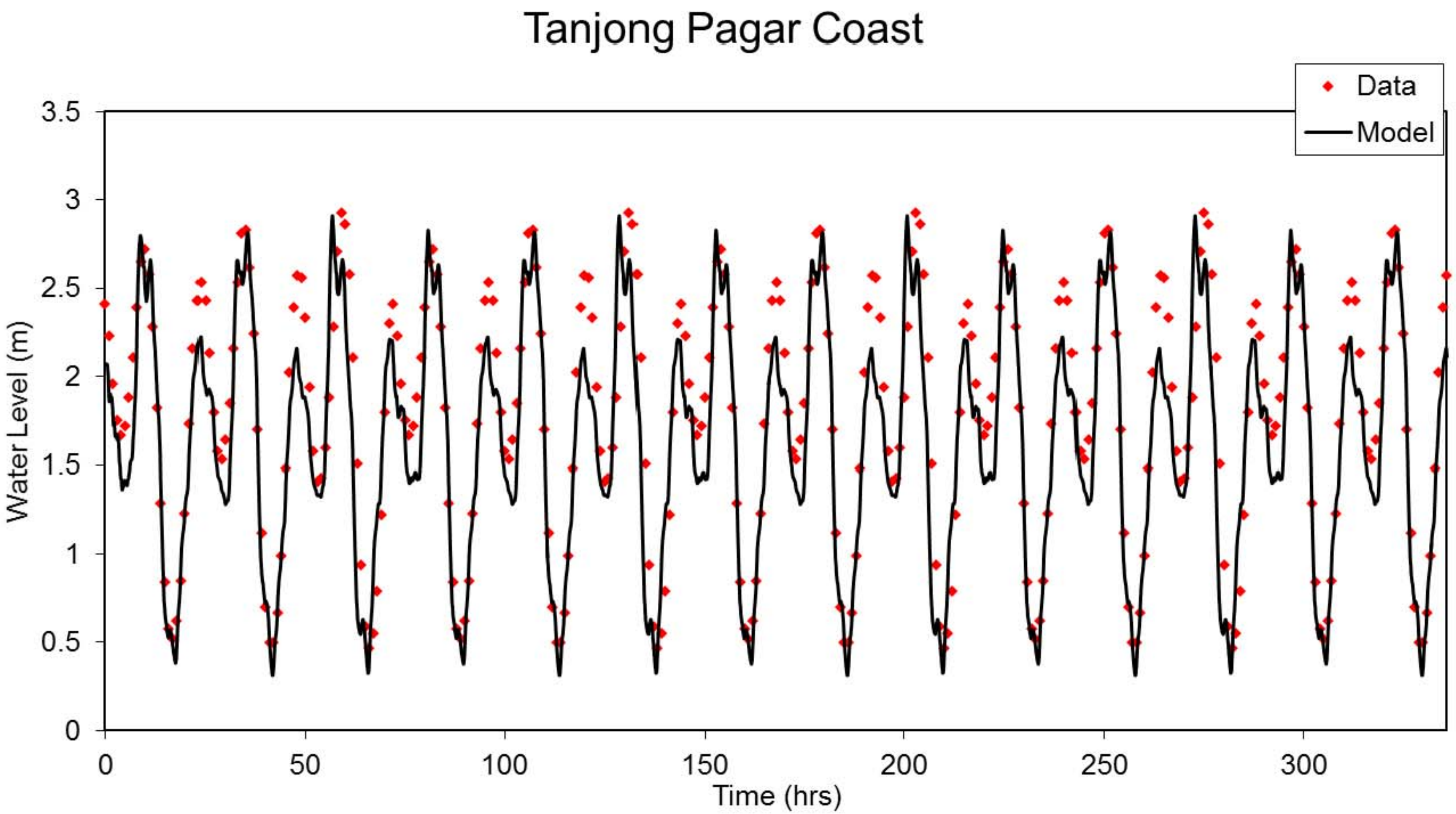

Figure 4. Tide level time history comparison of modelled and Admiralty data at location of Tanjong Pagar Coast (duration: 14 days from 1st to 14th February 2011)

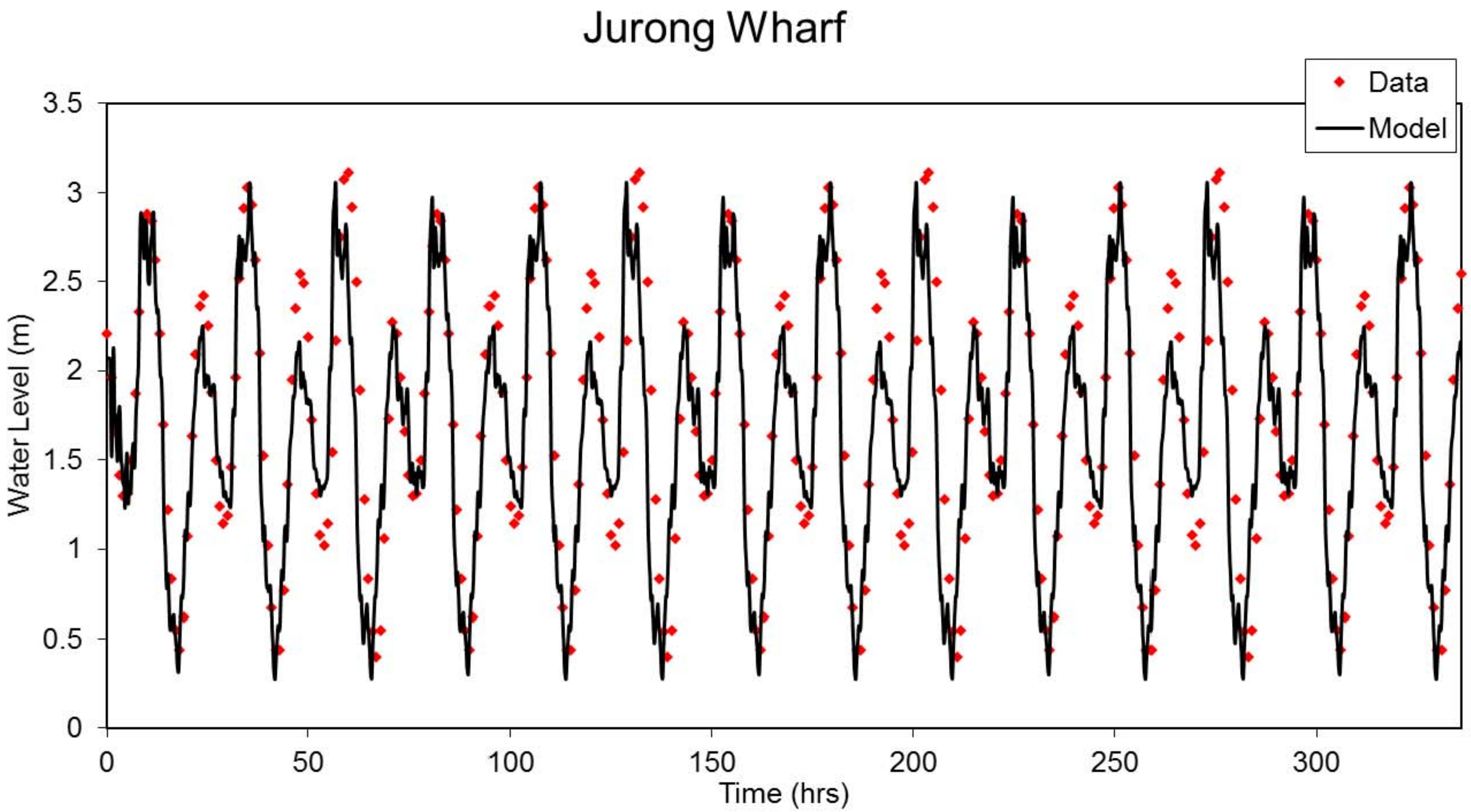

Figure 5. Tide level time history comparison of modelled and Admiralty data at location of Jurong Wharf (duration: 14 days from 1st to 14th February 2011)

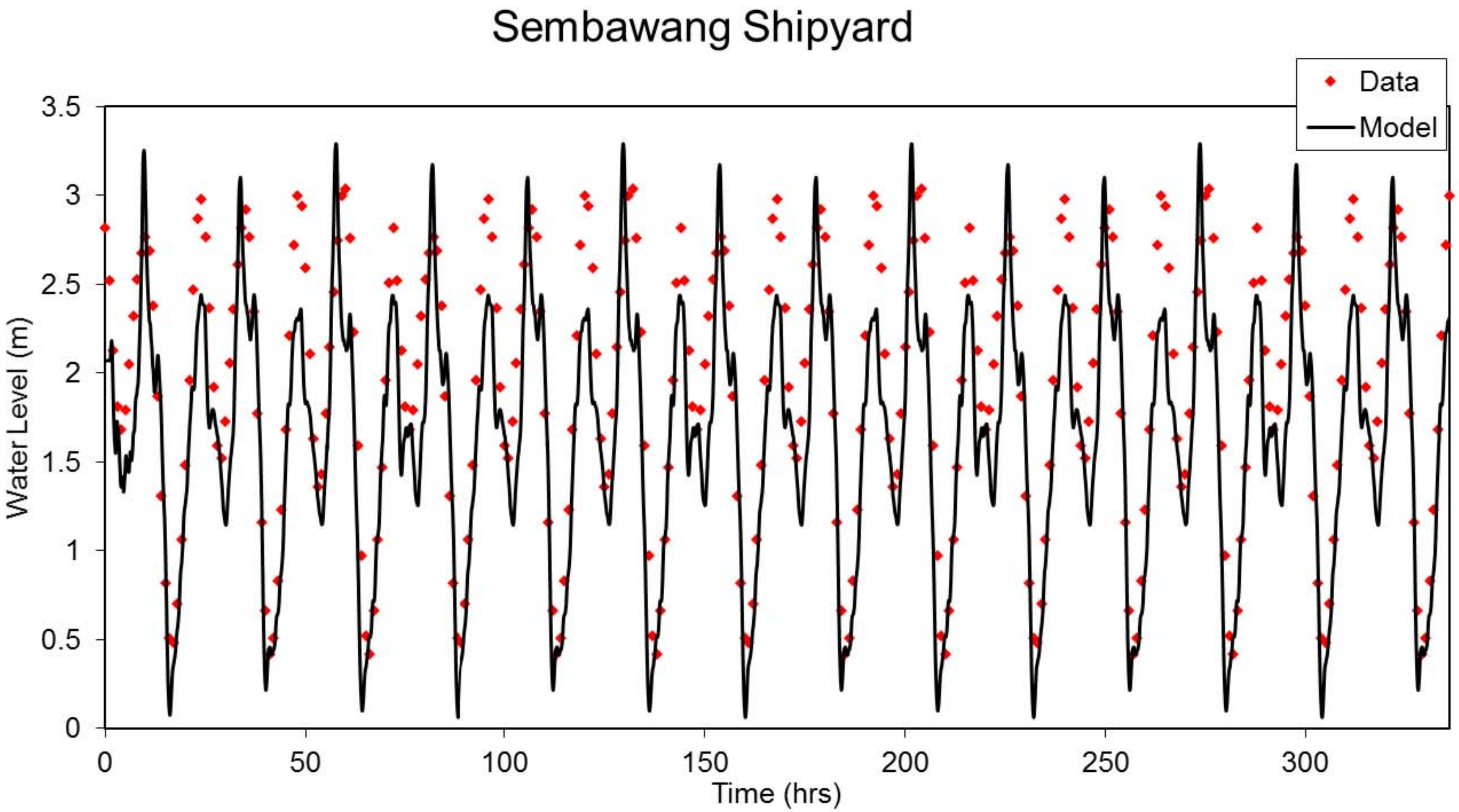

Figure 6. Tide level time history comparison of modelled and Admiralty data at location of Sembawang Shipyard (duration: 14 days from 1st to 14th February 2011)

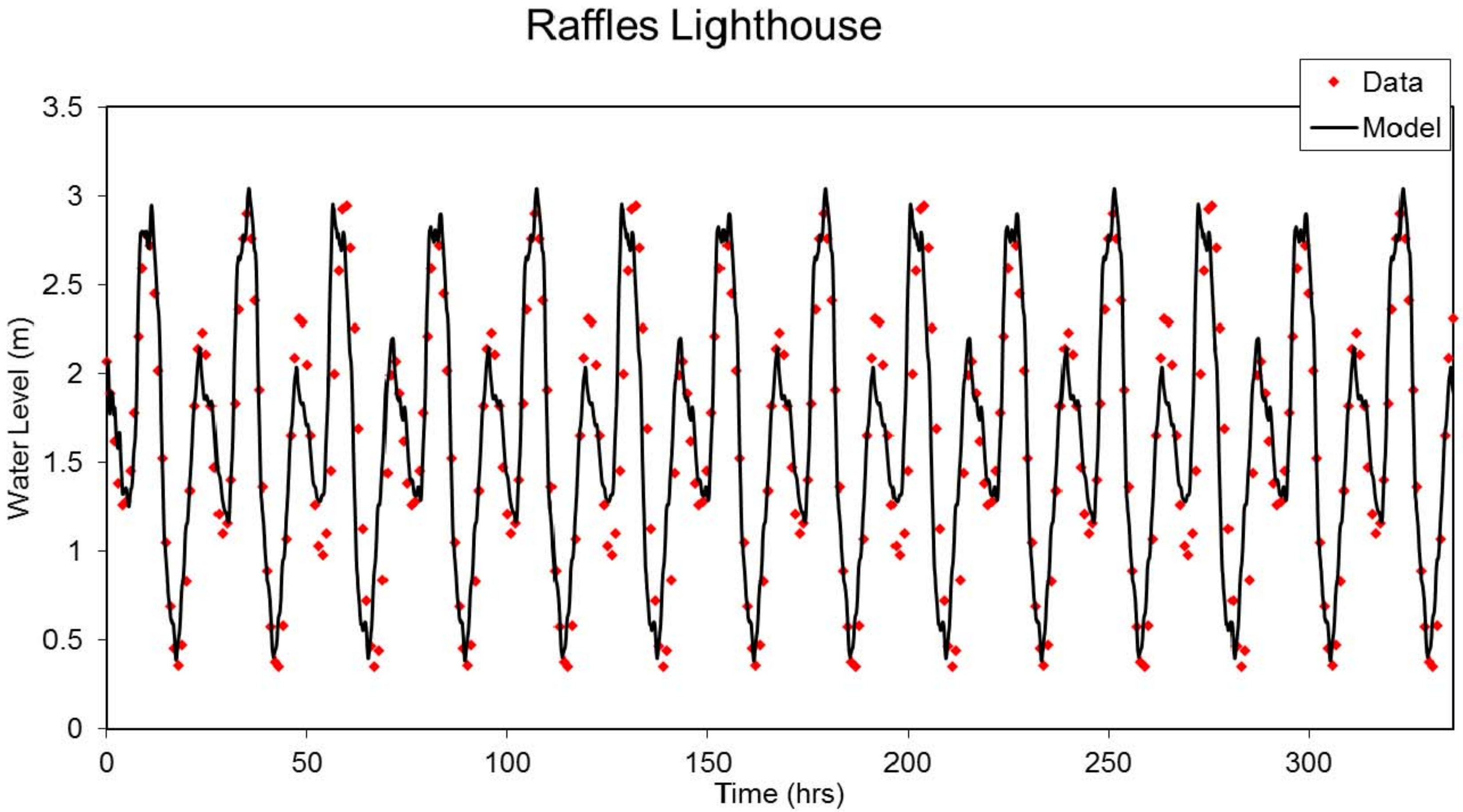

Figure 7. Tide level time history comparison of modelled and Admiralty data at location of Raffles Lighthouse (duration: 14 days from 1st to 14th February 2011)

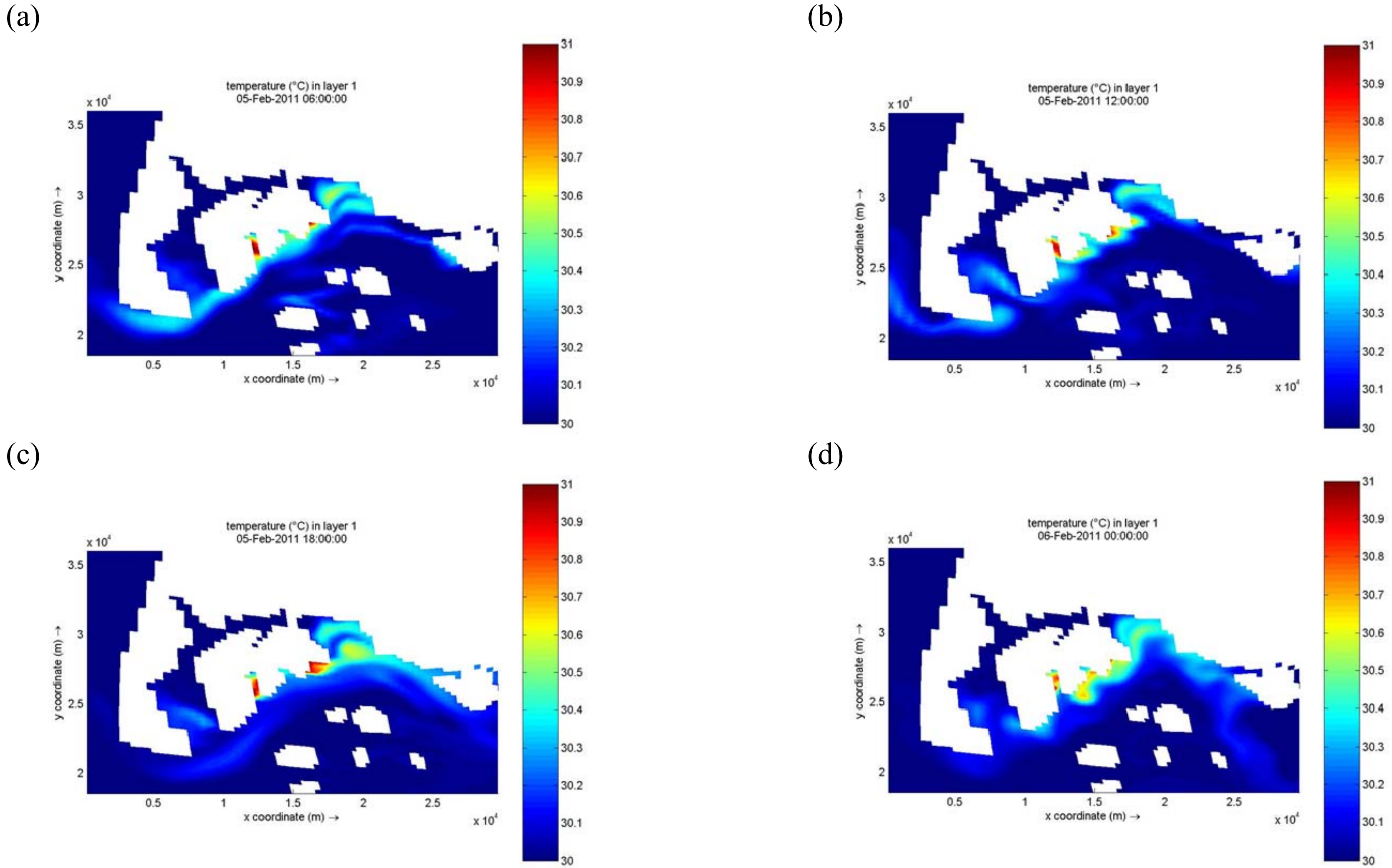

Figure 8. Thermal map daily cycle caused by the industrial discharges from Jurong Island

(a)

(b)

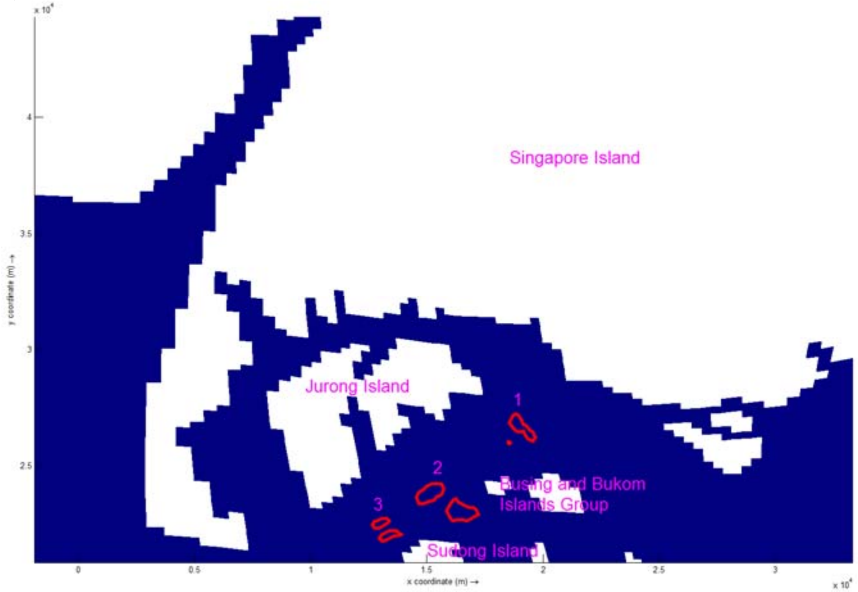

Figure 9. Coral map (a) measurements and (b) simulation comparison. In both figures, (1) represents the Cyrene Reefs, (2) represents the coral reefs near to Busing and Bukom Islands Group, and (3) represents the coral reefs near to Sudong Island. The measured coral map in Figure (a) are obtained from ReefBase [23].