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Lagrangian Model Simulation of Passive Tracer Dispersion in the Siak Estuary and Malacca Strait

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Abstract: The 3-dimension hydrodynamical Hamburg Shelf Ocean Model (HAMSOM) is used to study the dispersal of riverine pollutants in the Malacca Strait. Surface currents dominantly flow northward, i.e. from south eastern Java Sea to the Malacca Strait. The model simulations indicate particles discharged by the Siak River could reach the northern part of Bengkalis Strait within 20 days.

Key words: Malacca Strait, hydrodynamic modelling, circulation, pollutant dispersion, seasonality.

Introduction

Riau seawaters located in the southeastern part of the Malacca Strait are directly connected to the northern part of the Java Sea (see Figure 1). The dynamics are influenced by water masses from the Indian Ocean in the northern part of the Malacca Strait and by Java Sea and South China Sea water masses in the southern part.

The investigation area exhibits a pronounced seasonal reversal of the wind direction due to the strong influence of the monsoon. During winter (November to March) northeasterly winds dominate, whereas in summer (May to September) the main wind direction is from the southwest. Despite these changing meteorological forcing conditions the inter-annual variability of the flow field is relatively small. All over the year, the water mass transport is directed towards the Indian Ocean which is strongly related to the sea level gradient in this strait (Wyrtki, 1961). During the northeast monsoon, AVISO data indicate that the dynamic topography in the Java and South China Sea is higher than in the Andaman Sea (reference Aviso). In contrast, during the summer monsoon, the dynamic topography is nearly reversed, but this pressure gradient is compensated by southeasterly winds, which are responsible that also in this season the flow is directed towards the Indian Ocean. This permanent northward water mass transport in the Malacca Strait has been described in detail in Putri and Pohlmann (2009). Further information concerning the hydrodynamical variability of this area can also be found in Mayer and Pohlmann (Mayer and Pohlmann, 2014).

In addition to this residual flow a strong tidal influence can be observed, which is dominated by the M_2-tide as seen from its semi-diurnal period, with two flood and ebb events within one day.

Model Description

The circulation model applied in this study is a modified version of the three-dimensional, baroclinic Hamburg shelf ocean model (HAMSOM) developed by Backhaus (1985) and modified by Pohlmann (2006). A detailed description of the specific application of this model to

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the Malacca Strait can be found in Putri and Pohlmann (2009).

Model Setup

As the first step, HAMSOM was used to simulate a large model area from 2.5°S to 5.5°N and 95.5°E to 110.5°E, covering the Malacca Strait and the western part of the Java Sea (see insert in Figure 1). A nested model strategy is applied in this study by setting up a smaller model area covering the vicinity of the Siak River estuary from 0°N to 2°N and 101°10′E to 103°47′E with 315 × 241 grid cells. The horizontal resolution is 0.5′ (approximately 0.93 km) while vertically the water body is divided into nine layers, each having a thickness of 5 m. The maximum depth of the model area is 45 m. Open boundary values, namely sea surface elevation, temperature and salinity are taken from the outer model which covers the entire West-Indonesian waters. (For inner boundary see red box in Figure 1).

For both, the large scale and the small scale model simulations, eight tidal constituents are used, i.e., M_2, S_2, K_2, N_2, K_1, O_1, P_1 and Q_1 obtained from Zahel et al. (2000). The atmospheric forcing prescribed in this simulation are six-hourly atmospheric data from the National Center for Environmental Prediction (NCEP) (Kalnay et al., 1996). In particular, 2 m-air temperature, 10 m-zonal and meridional surface wind, specific humidity, surface pressure, cloud cover and precipitation data are employed. Climatological temperature and salinity data from the World Ocean Atlas 2001 (Conkright et al., 2002) are utilised as initial values.

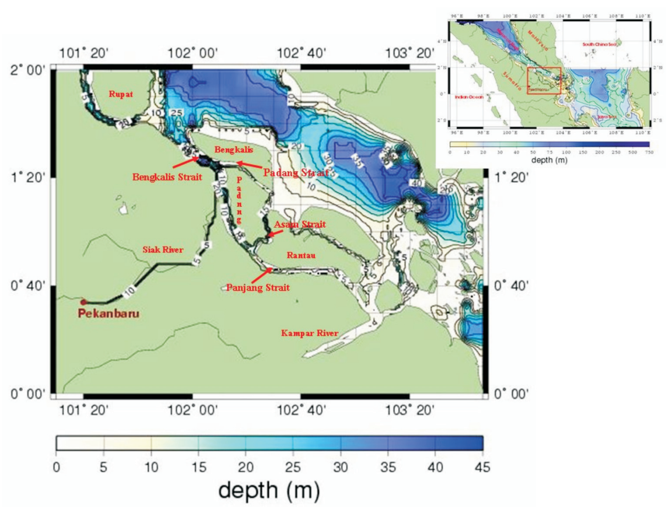

Figure 1: Bathymetry of Riau Waters (small upper right figure shows the location of the main investigation area (red box)).

Along the first 98 km of the Siak River from Pekanbaru to the estuary the salinity is set to 0.2 psu, whereas for the last 2 km, data observed during the measuring campaign in 2004 are prescribed. Moreover, in the small-scale model the influence of the fresh water discharge is considered. Monthly averaged discharge rates of the Siak River at Pekanbaru is about 100 m^3/s in the wet season during summer monsoon (May-September) and 45 m^3/s in the dry season during winter monsoon (November-March) (Pusat Penelitian Air, 1998). The monthly discharges in 1998 will be taken as representative for the entire simulation period of the small model.

General Description of the Transport Model

In principle it is possible to employ two different types of dispersion models, i.e., Eulerian and Lagrangian models. Both types have their advantages and disadvantages. The Eulerian model is more suitable to simulate widespread pollutants, while Lagrangian models are mainly used to trace single releases of a more localised character.

The basis of both model types is the three-dimensional transport equation for substances of concentration C which can be formulated as:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(A_h\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_h\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_v\frac{\partial C}{\partial z}\right)+\mathrm{Source}_C-\mathrm{Sink}_C$$

where u, v and w are the x, y and z velocity components, respectively; A_h and A_v are the horizontal and vertical diffusion coefficients; and $Source_C$ and $Sink_C$ are the internal and external source and sink terms for the respective substance.

In this current paper only results from Lagrangian dispersion models will be presented. In this formulation a specific number of tracers in a control volume represent a certain concentration. These tracers are advected in space by following their trajectories driven by the underlying velocity field. The latter is obtained from the three-dimensional circulation model (HAMSOM). In this scheme diffusion is described by means of the Monte-Carlo method which adds an additional random displacement to the individual tracer position.

In general, in the Lagrangian framework, the evolution of the position x of a specific particle is based on the following equation (for simplification only its displacement in x-direction is considered):

$$\frac{\partial x}{\partial t} = \vec{v} + \vec{v}_r$$

where $\vec{v}$ and $\vec{v}_r$ are the advective and the random velocity representing the diffusion, respectively. Numerical integration leads to:

$$x(t+1) = x(t) + (\vec{v} + \vec{v}_r) \cdot dt = x(t) + \vec{v} \cdot dt + r$$

where r being the specific random displacement of a certain particle. The bandwidth $\vec{r}$ of this random displacement is directly related to the diffusion coefficient A_h or A_v, respectively:

$$\vec{r} = \sqrt{6 \cdot A_{h/v} \cdot dt}$$

where dt is the time step of the dispersion model.

This proceeding requires a certain minimum amount of tracers to be released since otherwise the "diffusive cloud" is not representative for the diffusion process. In order to investigate the fate of different water masses, this complex dispersion model can also be downgraded to a simple tracer model by only employing the advective algorithm. In this case it can be applied to individual tracers since only the formulation of the diffusion process requires a larger number of tracers.

Simulation Set-Up of Trajectory Model

After obtaining the hydrodynamical parameters by running the HAMSOM model, the trajectory model is employed. The particles are always released in the centre of the surface layer, i.e. in 2.5 m depth and in the centre of respective input grid cell. This implicates that the observed diffusion of the particles is only caused by the Monte-Carlo method. Altogether three different scenario runs have been conducted:

1. A drift simulation with 50 particles including tidal current as the generating force. This simulation is used to observe the tidal influences to the trajectory of pollutants from the Siak River estuary only. The model is simulated for the period 25 to 30 March 2006 and the time step of the dispersion model is 180 s.
2. A drift simulation with 25 particles released from the Siak River estuary. The simulation is run from 20 to 30 March 2006 using daily averaged current.
3. A drift simulation with 200 particles released in the Siak River estuary, at the entrance of Bengkalis Strait, off the Padang Strait and in the central Malacca Strait. This simulation is conducted for the period 1 to 10 January 2006 again using the daily velocity fields.

Results and Discussion

Influences of Tidal Current

Riau waters are located in the zone where the diurnal tidal wave is dominated by K_1 from the Java Sea and the semi-diurnal tidal wave dominated by M_2 from the Indian Ocean converge. Generally, almost all over the year, the ocean currents are flowing north-westward (Wyrtki, 1961; Putri and Pohlmann, 2009). However, in the investigation area the semi-diurnal tidal wave dominate the tidal currents in this area, particularly close to the coast such as in the Siak River estuary.

Figure 2 depicts the semi-diurnal current pattern in the Riau waters. 4-5 hours after high water, the current flows northward from the Panjang Strait and in the same direction as water from the Siak River estuary. Furthermore, this current joins the current from the Malacca Strait flowing through the Padang Strait, and subsequently, flowing out of the Bengkalis Strait into the Malacca Straits. During ebb tide, i.e. 6-7 hours later, currents are directed southward from the Malacca to the Bengkalis Strait, part of the flow enters the Padang Strait and turns back to the Malacca Strait. Another branch flows southward into the Siak Rivers and Panjang Strait. This alternating current pattern reoccurs twice a day.

The average magnitude of surface current during flood condition in the Bengkalis Strait is between 0.6 and 0.7 m/s flowing southward. On the other hand, during ebb conditions, the average magnitude of surface current is smaller, i.e. between 0.4 and 0.5 m/s flowing northward. This relation indicates that water fluxes from Malacca Strait to the Siak River during flood conditions are higher than those during ebb conditions. This is compensated by the fact, that the duration of the ebb tide (7-8 hours) is longer than of the flood tide (5-6 hours).

The direction of the water mass transport can be visualized by the movement of released particles in front of Siak River estuary (see Figure 3). At the beginning when the particles are released, i.e., on 25 March 2006 at 10.00, it appears that until 17.00 (Figure 3a and 3b), almost all particles move northward and can be transported as far as 2.5 km north of the Siak River mouth, in accordance with surface current direction (Figure 2a). At 21.00 during flood conditions, particles are moving into the opposite direction, i.e., southward (Figure 3c) until 26 March 2006 at 03.00 (Figure 3d) with a maximum travel distance of less than 2 km. This transport is in agreement with the velocity direction during flood tide (Figure 2b). When the current flows northward, almost all of 50 released particles are

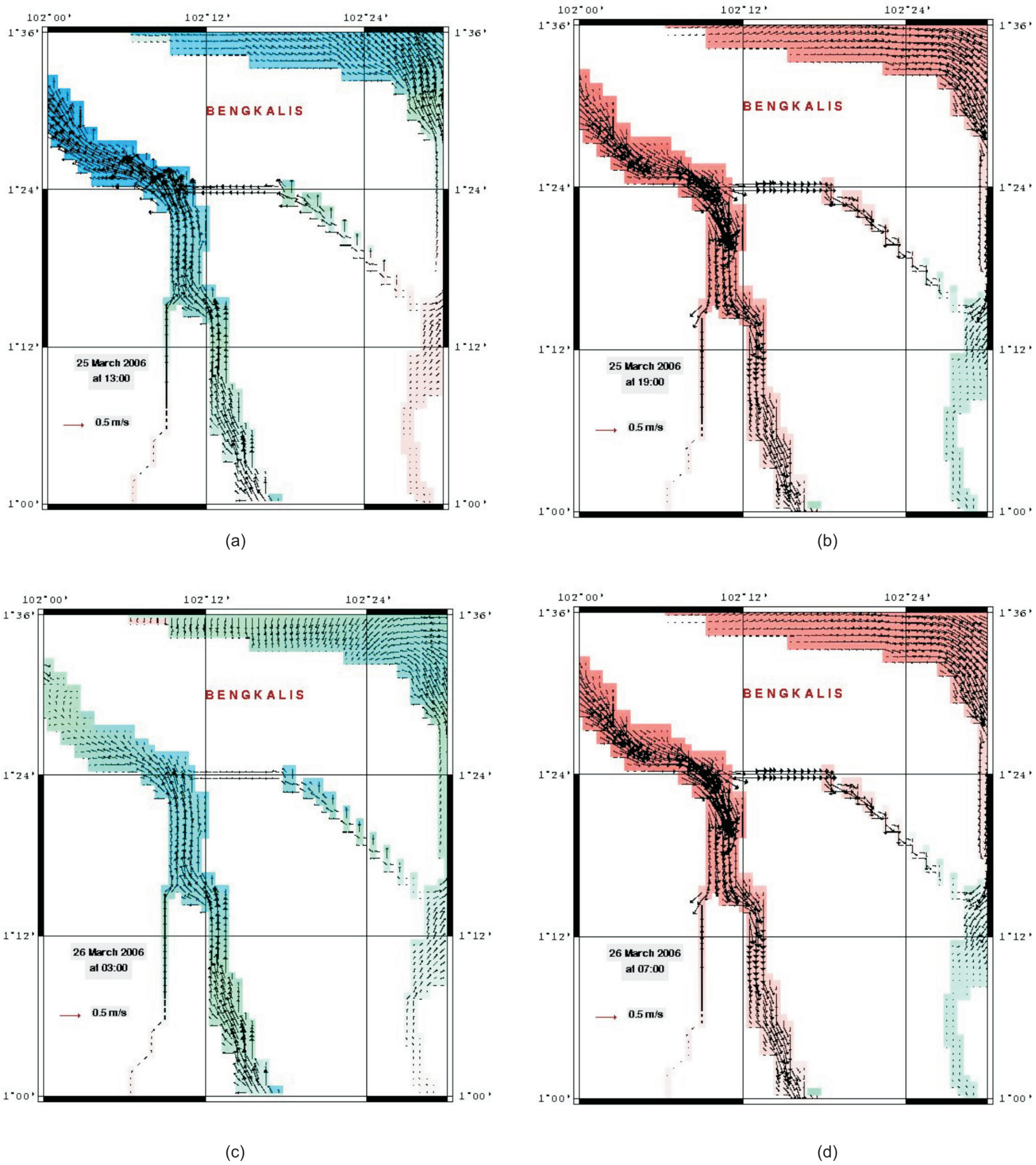

Figure 2: Sea Surface Current in the Siak River Estuary at 13 h, 19 h on March 25 and 3h, 7h on March 26, 2006 (colour shading represents sea surface displacement, blue: low, red: high) (for scale see Figure 4).

moving northward, but when the current subsequently flows southward, about 10 to 25% of the particles remain north of the release location. This phenomenon shows that the northward movement is more dominant (Putri and Pohlmann, 2009), and hence it can be estimated that pollutants will spread predominantly northward in the Bengkalis Strait, as a result of the residual circulation.

Influence of Daily Averaged Current

Particles Released in the Mouth of Siak River and Bengkalis Strait

Figure 4 depicts particle trajectories which are transported by means of daily averaged ocean current. Already after five days, particles released in the Siak River estuary have moved northward up to the Padang

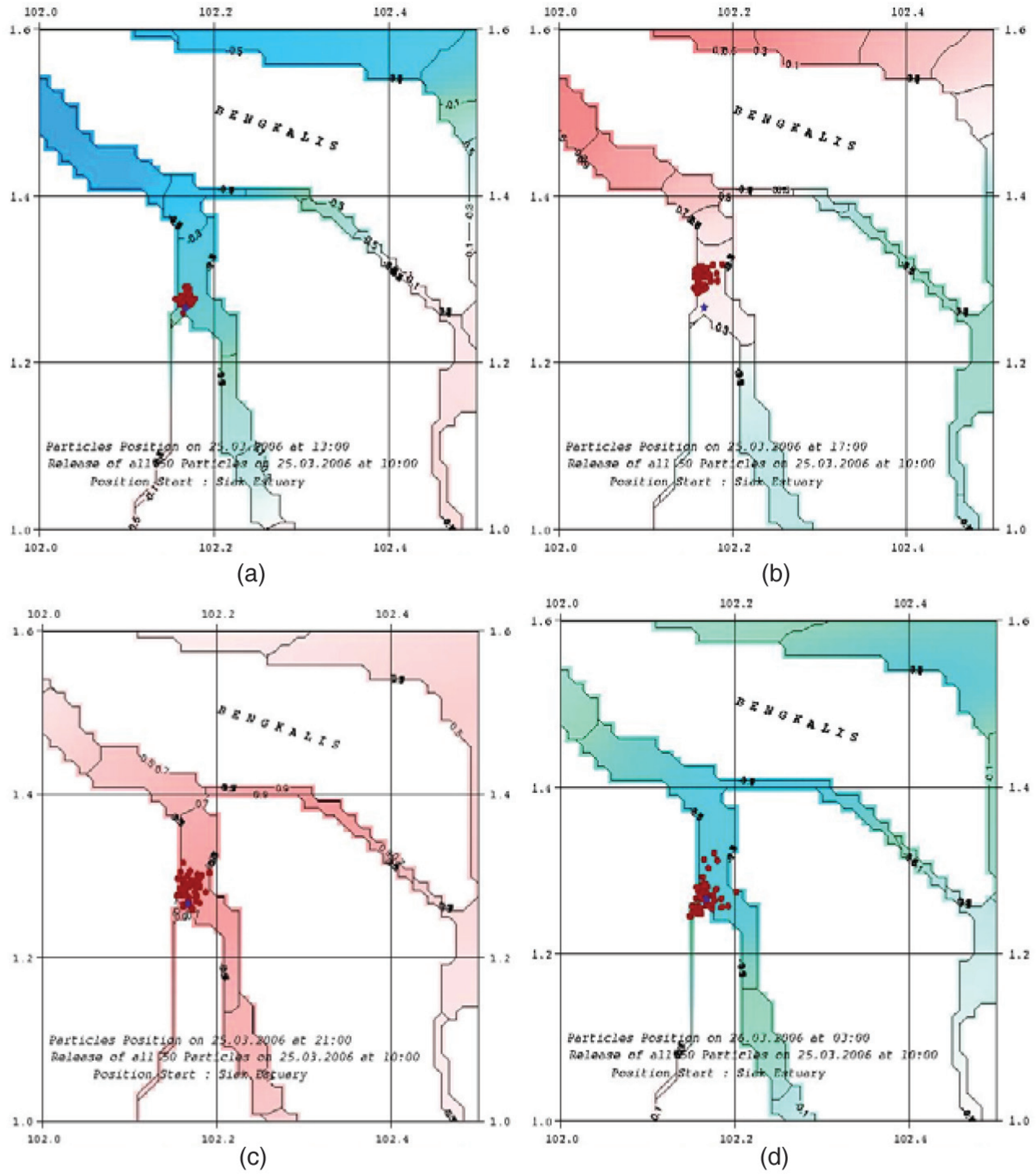

Figure 3: Trajectory of 50 particles displayed at 13 h, 17 h, 21 h on March 25 and 3h on March 26, 2006 (all particles were released on March 25, 2006 at 10 h in the Siak River Estuary) (colour shading represents sea surface displacement, blue: low, red: high) (for scale see Figure 4).

Strait. In contrast, only 10% of the particles have moved southward.

Figure 5a shows the position of particles released in the mouth of Siak River after 10 days of simulation. Almost all of the particles have moved northward and have reached the western entrance of the Bengkalis Strait. Only a small part of the particles have spread southward by less than 1-2 km from the Siak estuary and very few of them entered the Padang Strait.

These results calculated from daily averaged ocean currents, are in agreement with results of the tidal resolving simulation when the water masses exhibit an alternating flow characteristic. In both cases the dominant residual flow is directed to the north.

Meanwhile, for the Bengkalis Strait release (Figure 5b), it can be seen that the introduced particles reach further north into the open Malacca Strait (approx. 100 km in 10 days). From these results (as depicted

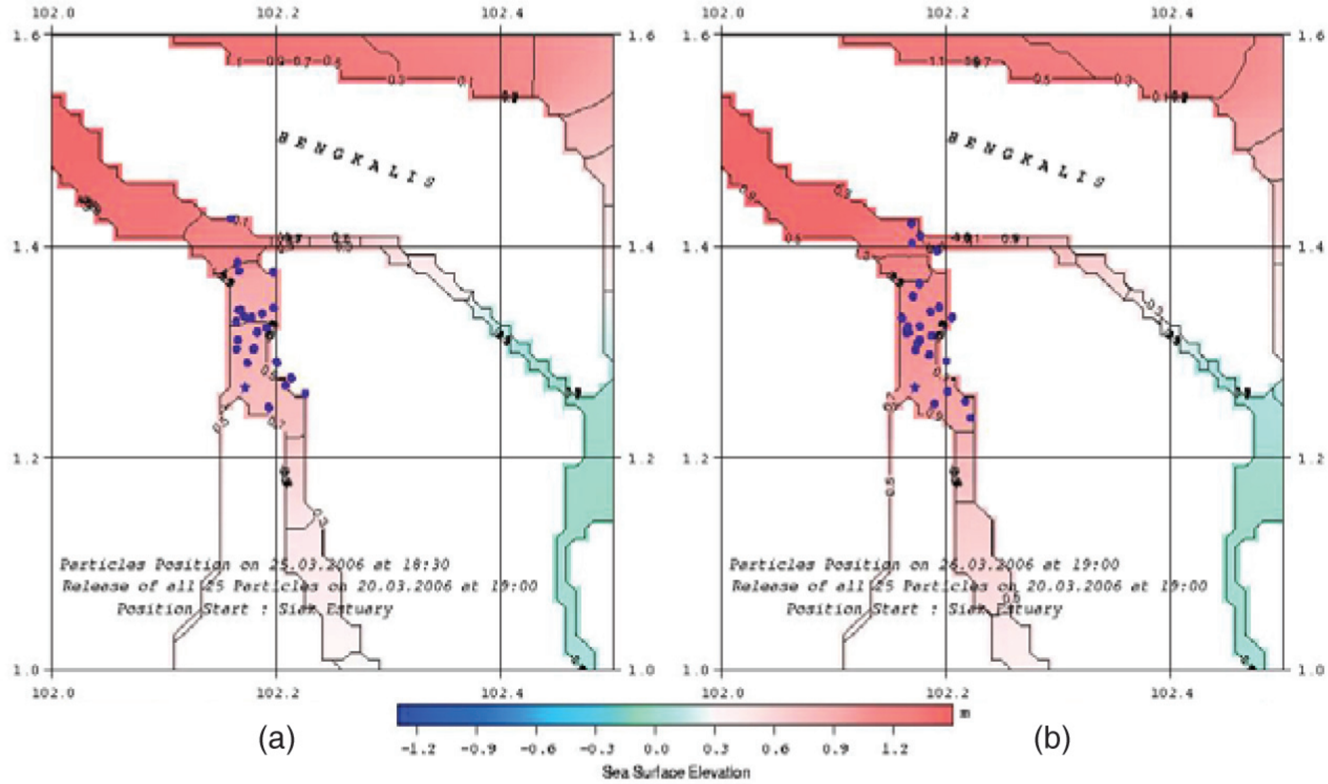

Figure 4: Distribution of 25 particles released on March 20, 2006 at 19:00: (a) Particles position after five days and (b) after six days (colour shading represents sea surface displacement, blue: low, red: high).

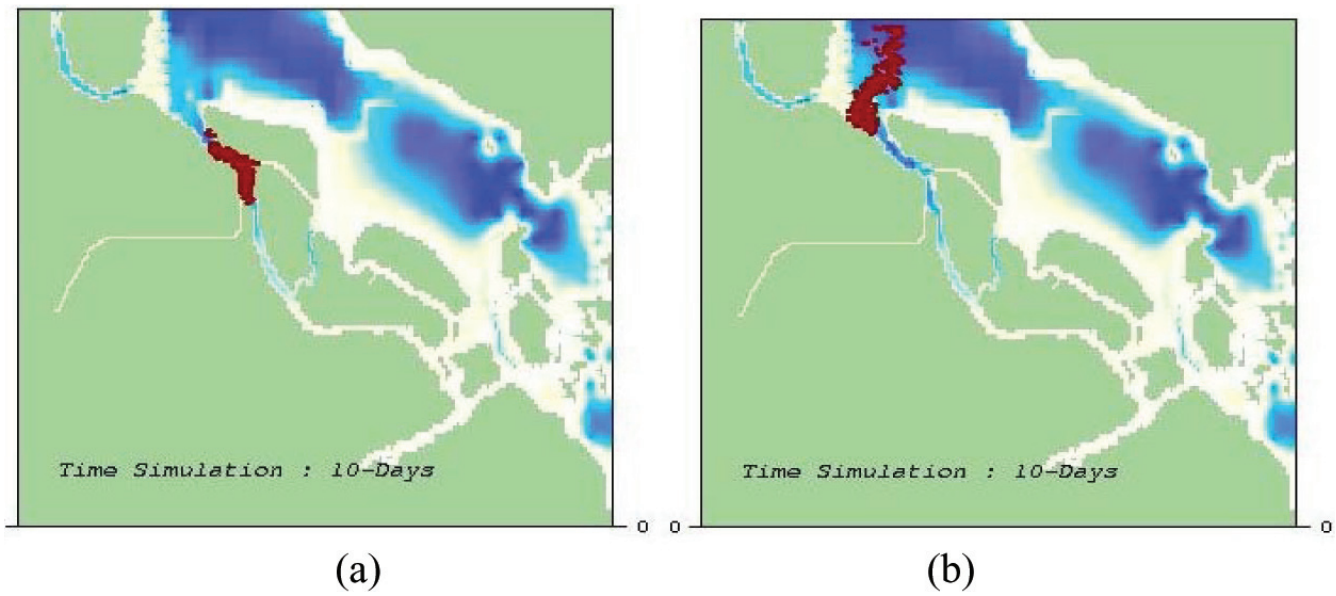

Figure 5: Trajectory of 200 particles released on 1-10 January 2005: (a) in the mouth of Siak River estuary and (b) in the entrance of Bengkalis Strait.

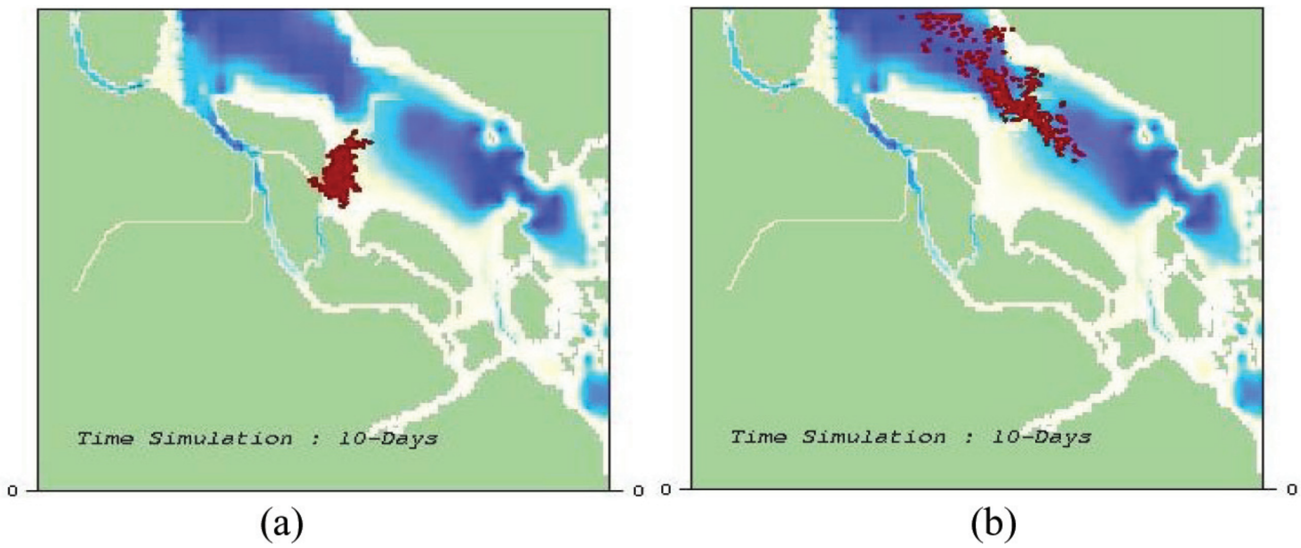

Figure 6: Trajectory of 200 particles released on 1-10 January 2005: (a) in the eastern of Padang Strait and (b) in the central Malacca Strait (blue colour shading represents water depth (light blue: shallow; dark blue: deep).

in Figures 4 and 5), it can be predicted that pollutants from the estuary of Siak River would spread to the open Malacca Strait within a period of approximately 20 days.

Particles released at the eastern Padang and Malacca Straits

The sea level difference between the Java Sea and the Indian Ocean causes a predominantly northward flow in the Malacca Strait. Therefore, the seawater properties of the Java Sea with low salinity are dominating the southeastern part of the Malacca Strait (Putri and Pohlmann, 2009). Results of the trajectory model in the east of the Padang and Malacca Straits can be found in Figure 6. After 10 days, particles that were released in the east of the Padang Strait spread northward and reach the central part of the Malacca Strait (Figure 6a). Whereas, particles released in the centre of the Malacca Strait, after 10 days have reached the northern model boundary (Figure 6b). This means that the particles can be transported to the northern part of Malacca Strait by dominantly northward ocean current throughout the year.

Conclusion

From this work, it could be concluded that the HAMSOM model is able to reproduce the hydrodynamical conditions in the Riau waters reasonably well. Daily ocean current are strongly influenced by semi-diurnal tides with a strong asymmetry of flood and ebb periods. In the Bengkalis Strait, during flood condition the current flows from north to south entering the Siak River with a speed of 0.6 to 0.7 m/s for 4 to 5 hours. In contrast, during ebb tide the flow is directed in the opposite direction for 6 to 7 hours, with values lying between 0.4 and 0.5 m/s. Due to the residual flow, particles from the Siak River on the long-term move northward and reach the Malacca Strait in approximately 20 days.

Acknowledgements

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