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# Seasonal variations in circulation and average residence time of the Bangpakong estuary, Thailand

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**Abstract** : Seasonal variations in 3-dimensional circulation and average residence time of conservative and passive tracer in the Bangpakong estuary were investigated using the Princeton Ocean Model (POM) and the Euler-Largrange method. Observed salinity and temperature, average wind velocity and river discharge, and calculated tidal elevation were significant inputs for computation. The results indicated that all driving forces interacted complicatedly to the seasonal variation of circulation in the estuary. Wind-driven current is predominant and its magnitude is large at the sea surface while tidal prevalence is observed throughout the water column. Influence of river discharges as an outflow and density-driven current is also observed near the river mouth during wet season. The tracer experiment indicated that tidal current played an important role to move particles out of the estuary in a short time and seasonal variation in residence time depended on variations in wind-driven circulation, tide and river discharge. Calculated residence times from the longest to the shortest are 29.1 days, 20.8 days, 10.8 days and 6.0 days in April, June, December and September, respectively, corresponding to those from a box model analysis based on the mass balance of salt using the same salinity and discharge data.

***Keywords :*** *circulation, residence time, POM, Bangpakong estuary, Gulf of Thailand*

## 1. Introduction

The Bangpakong estuary is an estuary located in the northeastern corner of the upper Gulf of Thailand (Fig. 1) and is a highly eutrophic area where blooming of phytoplankton frequently occurs. Much nutrients and organic substances from the Bangpakong river are supposed to be the cause of the eutrophication in the estuary and surrounding areas (NRCT-JSPS, 1998, JINTASAERANEE *el al.*, 2000 and BURANAPRATHEPRAT *et al.*, 2002). However, we have not yet known the mechanism of the eutrophication because of complicated physical characteristics of this estuary. They are due to its shallowness, river discharge, tide and wind which interact intricately under strong seasonal variations. Therefore, if we do not understand well these entire mechanisms, we may not succeed in understanding the phenomena occurring in this estuary.

TAKEOKA and HASHIMOTO (1988) noted that transport of matter in coastal waters was an important subject relating to water quality problems, and that of nitrogen, phosphorus or carbon was especially important relating to eutrophication problems, which often spoiled the marine environment or even caused red tides or anoxic water masses. From this reason, circulation in the study area must be investigated because the results can be applied for further specific studies in terms of material transport, which help us to understand the

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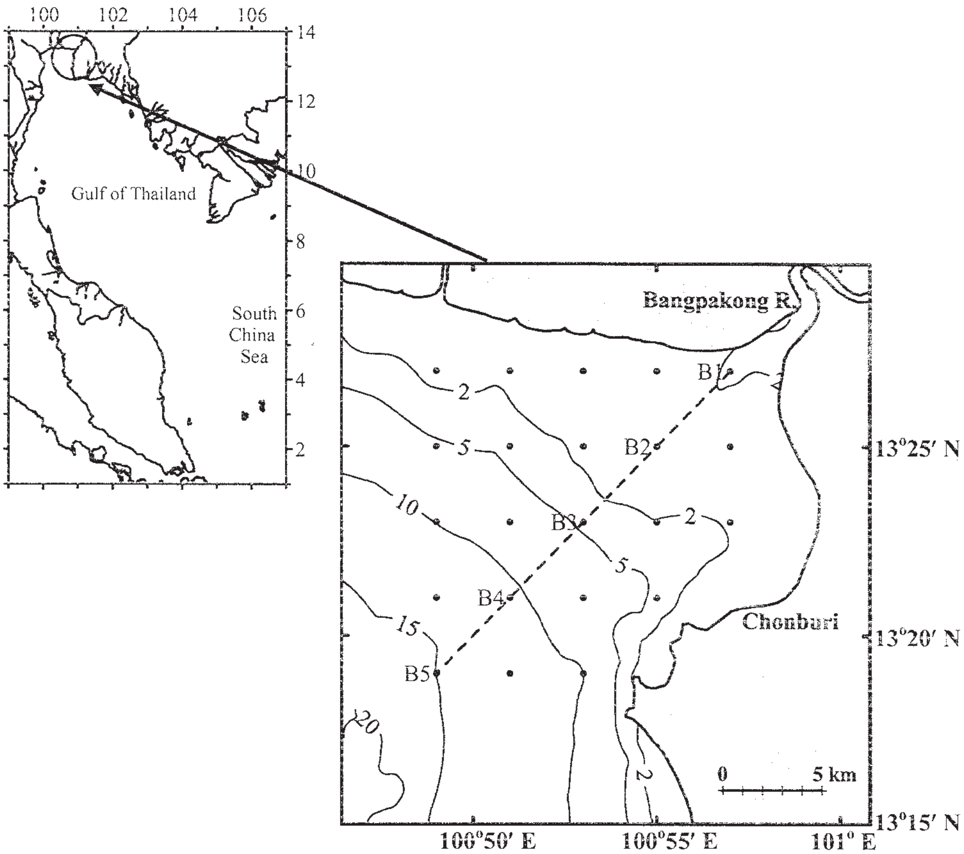


Fig. 1. The Bangpakong estuary and its bathymetry in meters, dots and a broken line represent observation points and the B-stations for vertical distributions, respectively.

behavior of materials in an estuary. Buranapratheprat and Yanagi (2000) tried to calculate vertical circulation of the Bangpakong estuary using a vertical 2-dimensional diagnostic model. Unfortunately, this model could not reproduce strong horizontal circulation generated by wind and river discharge that had 3-dimensional structure. They suggested that only 3-dimensional hydrodynamic model should succeed to reproduce circulation generated by all significant driving forces. Therefore, in this study, we will use a 3-dimensional hydrodynamic model, the Princeton Ocean Model (POM), to investigate the circulation in the Bangpakong estuary.

Residence time of material in an estuary is a significant physical characteristic. It depends on the exchange time of the material in the area (Yanagi, 1999a). Longer residence time of any material means more opportunity of the material to interact physically, chemically or biologically with surrounding water. For instance, if inorganic nutrients carried by river water into an estuary have long residence time, any plants and phytoplanktons living there will have more chance to use them for their photosynthesis. Buranapratheprat *et al.* (2002) used a box model based on the mass balance of salt to investigate the seasonal variation in residence time of fresh water in the Bangpakong estuary. They found that long residence time appeared during the transition period between dry and wet seasons, and wet and dry seasons. Short residence times were observed in mid-seasons, dry and wet seasons. They suggested that such results occurred from interaction between river discharge varying seasonally and tidal force. This hypothesis needs proofing because the box model in that study can not elucidate in details what is really occurring or what are the actual factors governing the phenomenon. Therefore, we will calculate the residence time of material in the estuary in terms of passive tracer experiment using POM to confirm the results of the previous study and to investigate the mechanism of material transport in the Bangpakong estuary.

## 2. Field observations

Field observations in the Bangpakong estuary were conducted four times according to seasonal variation in river discharge presented in BURANAPRATHEPRAT *et al.* (2002). They are the dry season (5 and 7 April 2002), the transition period from dry to wet seasons (15–16 June 2002), the wet season (13–14 September 2002), and the transition period from wet to dry seasons (13–14 December 2002). Figure 1 shows sampling stations (dots) covering the entire estuary and a broken line in central part of the area (B-stations) indicates stations for vertical distributions. Salinity and temperature were measured from the sea surface to the bottom every 0.5 meter using a CTD/STD meter (Sensor Data model SD204). These data including calculated density in terms of sigma-t ($\sigma_t$) are used to study the horizontal and vertical distributions of these parameters in the estuary. The observed salinity and temperature are also employed in POM as computational inputs for the circulation and the tracer experiment.

Seasonal variations in horizontal distributions of salinity, temperature and density at the sea surface are illustrated in Fig. 2. Temporal changes in salinity and density depended on the river discharge, while that in temperature was not prominent because the area was located in the tropical zone. The lowest sea surface water temperature was around 28℃ and the highest was around 32℃ in December and June, which were wintertime and summertime, respectively. Lowest salinity but highest gradient in sea surface salinity appeared in September while highest salinity but lowest gradient occurred in April. The salinity distributions also showed the penetration of fresh water into the northwest of the area in April and June. We can observe the plume obviously in April when sea surface salinity is high in almost area but low salinity emerges just in the northwest. In December, the distribution of sea surface salinity showed a plume of fresh water from the Bangpakong river having trend to the west more than to the south of the river mouth.

Seasonal variations in vertical distributions of salinity and temperature along B-stations in Fig. 1 are presented in Fig. 3. Vertical distribution of density is not shown because it varies in the same way as that of salinity (Fig. 2). As a result, the density variation will be discussed from the salinity distribution. Temperature near the river mouth at the sea surface was higher than that near the sea boundary in all seasons except December which was wintertime. It might depend on the difference in temperature between land and sea which was not quite large and fresh water from land was a little colder than outside seawater in wintertime. Vertical distribution of salinity also showed seasonal interaction of river water and seawater. Seawater intruded into the river during the time of low river discharge in April causing high salinity near the river mouth. On the other hand, salinity became much lower in June and September when river discharge was very large. In both seasons, fresh water from the river floated over salty water while going further from the river mouth to the sea which was the major cause of stratification there. Salinity gradient was largest in September due to the largest magnitude of river discharge at this time.

A scene of transition period from wet to dry seasons appeared in the vertical distribution of salinity in December when the river discharge became smaller. Intrusion of fresh water from another source outside the study area was also observed in the vertical distribution of salinity in April. When we consider with the horizontal distributions of surface salinity and surface density in April (Fig. 2), the contour line of 29 psu in Fig.3 suggests the fresh water intrusion from the west.

## 3. Circulation model

The Princeton Ocean Model (POM) is applied to calculate the 3-dimensional circulation of the

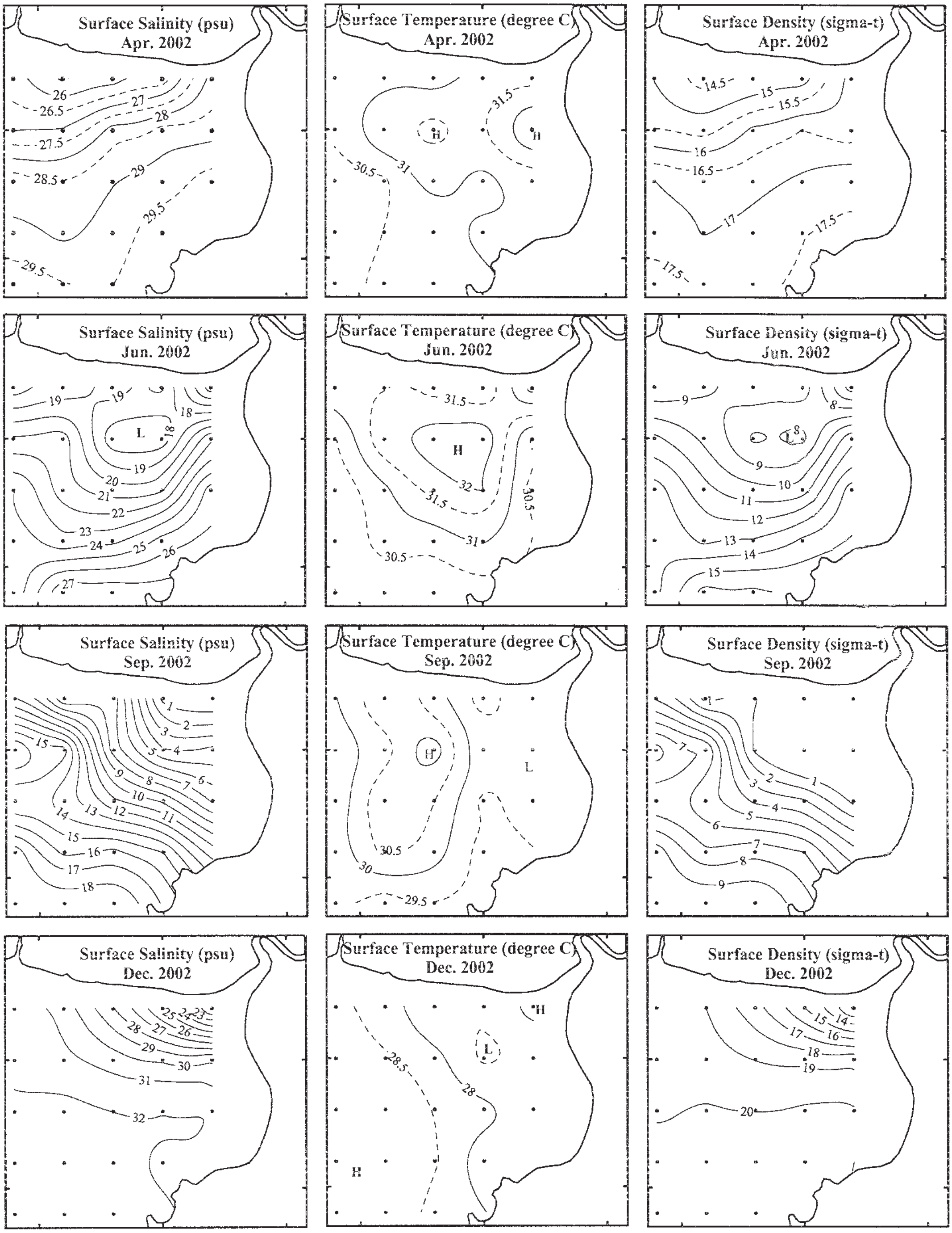


Fig. 2. Seasonal variations in surface distributions of water temperature, salinity and density (sigma-t). Dots show the observation stations.

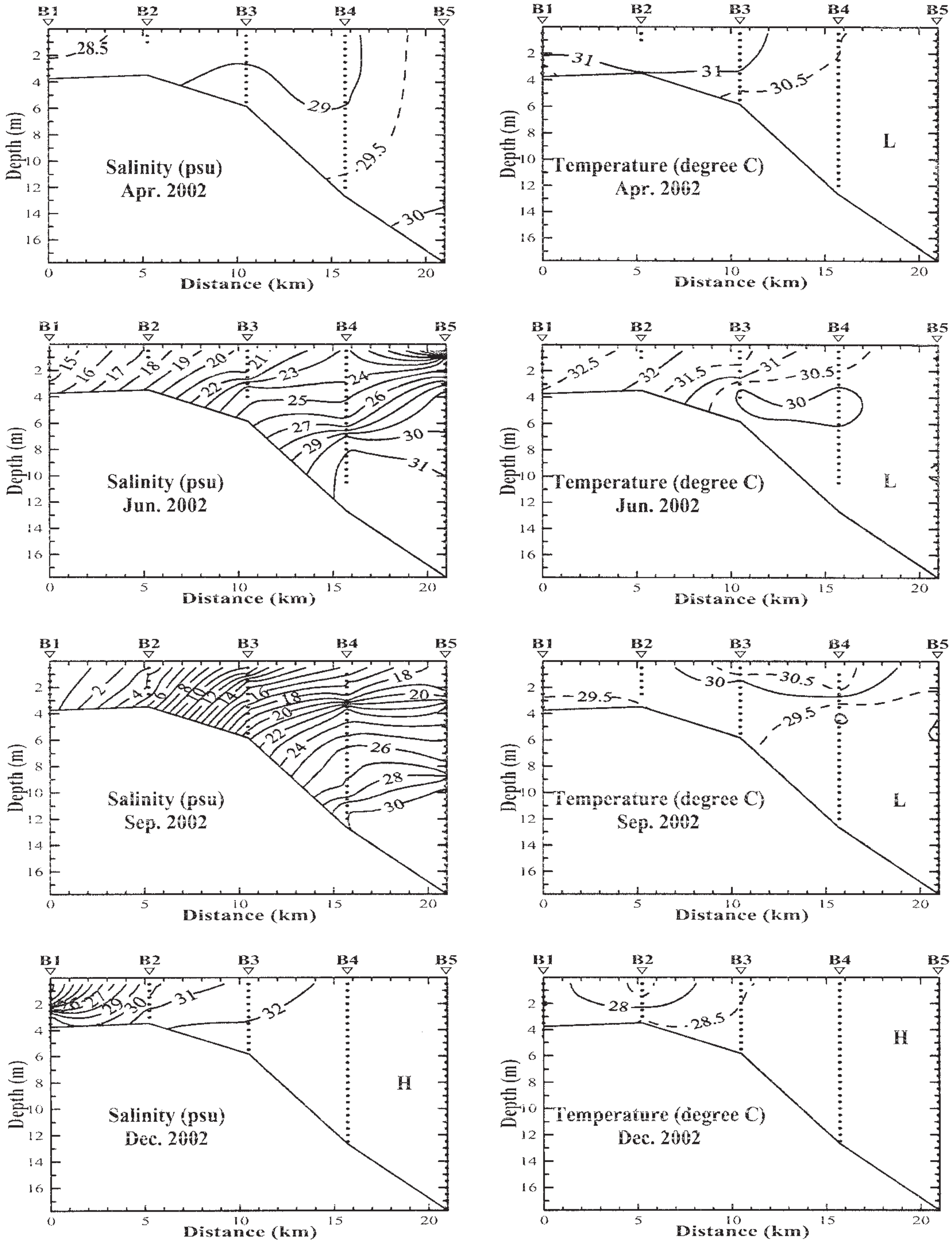


Fig. 3. Seasonal variations in vertical distributions of water temperature and salinity along the B-stations. Dots show the observation points.

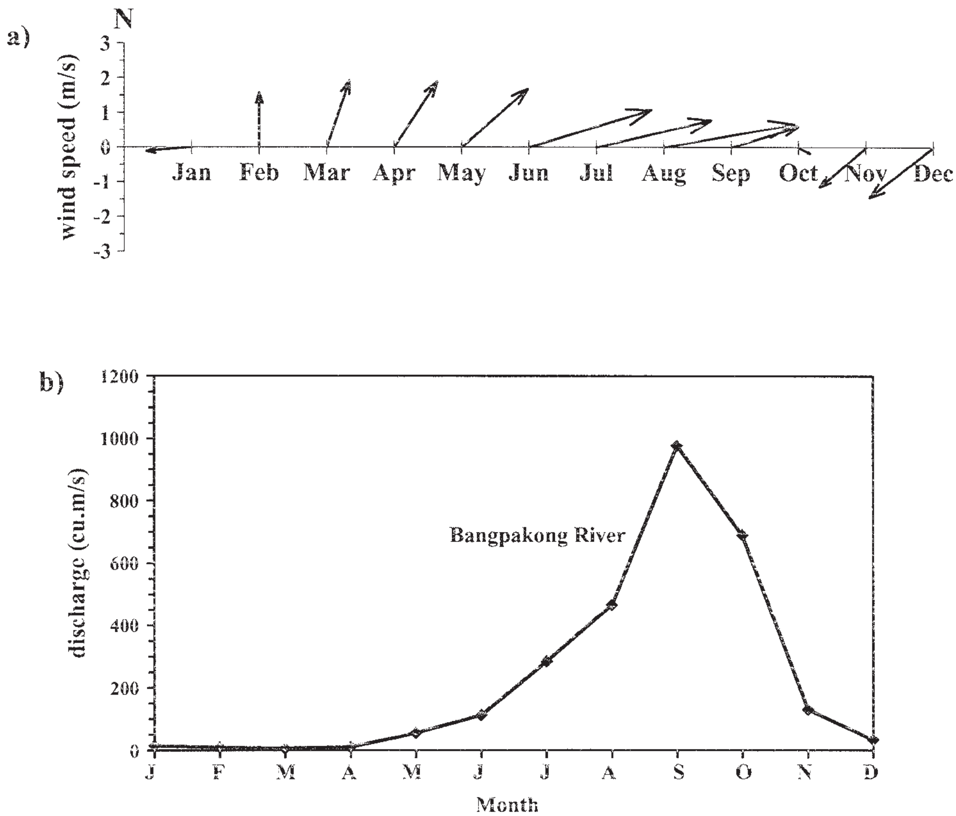


Fig. 4. Seasonal variations in average wind velocity over the Bangpakong estuary (applied from BURANAPRATHEPRAT and BUNPAPONG (1998)) (a) and average discharge of the Bangpakong River (BURANAPRATHEPRAT *et al.*, 2002) (b) .

Bangpaking estuary. The governing equations of the model consist of conservation of mass, momentum, salinity and temperature under the hydrostatic and Boussinesq approximations written in a bottom-following, sigma coordinate system (BALOTRO *et al.*, 2002). The model has a free surface and a split time step. The external mode portion of the model is 2-dimensional and uses a short time step based on the Courant-Friedrichs-Levi (CFL) condition and the external wave speed. The internal mode is 3-dimensional and uses a long time step based on the CFL condition and the internal wave speed (MELLOR, 1998). Vertical mixing coefficient is calculated in an imbedded second moment turbulence closure sub-model, while the Smagorinski diffusivity equation is applied for horizontal diffusivity. POM is a sigma coordinate model in that the vertical coordinate is scaled on the water column depth. Although the horizontal grid uses curvilinear orthogonal coordinates, it is easy for users to apply another horizontal grid system such as orthogonal and spherical coordinates. More details in POM including mathematical description are referred to BLUMBERG and MELLOR (1987), and MELLOR (1998).

The estuary area is divided horizontally into $37 \times 37$ grids in the spherical coordinate with grid spacing $0.5 \times 0.5$ minutes in latitude and longitude, respectively. The vertical domain is divided into 10 $\sigma$-levels with no logarithmic portions. Bathymetry data of the Bangpakong estuary are digitized from the navigation chart produced by the Royal Thai Navy. Salinity and temperature data from the observations are interpolated horizontally using Gaussian interpolation and vertically using linear interpolation to fit all grid spacing of the computational domain. Average discharge of the Bangpakong river (Fig. 4b) conditioned at the river boundary is from the study of BURANAPRATHEPRAT *et al.* (2002), and the average wind velocity (Fig. 4a) is estimated from that of BURANAPRATHEPRAT and BUNPAPONG (1998), because the river discharge and wind data in 2002 have not been published yet. As the meteorological condition in 2002 was not unusual, the employing average river discharge and wind data will not become a serious problem. Tidal stress calculation from tidal calculation (BURANAPRATHEPRAT *et al.*, 2003) is also included in this model.

Normal components of velocity to land boundary are set to be zero while radiation condition is assigned along open boundary in the internal mode that is also used as boundary condition along the open boundary for salinity and temperature. Tidal force in terms of water elevation along the open boundary is extracted from computational results of a 2-dimensional hydrodynamic model from the study of BURANAPRATHEPRAT *et al.* (2003), and it is updated in POM every external time step. The model is operated in diagnostic mode called the robust diagnostic mode where a damping term is added to the conservation equations of temperature and salinity. Please see more details in BALOTRO *et al.* (2002). Seawater state is set at rest at initial time of model operation ($t = 0$). Time steps are 3 seconds and 45 seconds for the external mode and the internal mode, respectively. The model is forced by wind, tide and river discharge from initial state until reaching a quasi-steady state 30 days after the beginning of calculation. Computed circulations from 30 days to 60 days are averaged to present the residual circulation of the estuary.

Seasonal variations in circulation of the estuary at the sea surface (0.5 m), 5.0 m depth and 8.0 m depth are presented in Fig. 5a and 5b. Wind driven current is predominant at the sea surface and has a strong seasonal change while tide-induced residual current influences over entire water column. Current induced by river discharge could be observed near the river mouth during the time of relatively large discharge especially in September. Surface current is quite complicated and not so strong with a tendency of flow into the river mouth following wind direction in April. Many small and weak eddies also appear throughout the area. At 5.0m and 8.0 m depths, two eddies, a clockwise and an anti-clockwise, are generated near west and south boundaries, respectively. Current in these deeper layers inside the area is very weak and tend to flow seaward in southwest direction.

Surface current seems very strong in June (Fig. 5a lower panel) because wind speed is strongest over other seasons during this time. There is a strong flow coming into the area through the north of west boundary being in line with wind direction. This flow is then separated into two parts; one moves directly further into the inner estuary reaching the east coast, while the other bends to the south and flows out of the area through south boundary. A weak outflow by the river discharge is observable at the east coast near the river mouth. This river flow then converges with current coming from the southwest which is supposed to be a part of separated flows coming through the west boundary. There is only an area in the northern coast that current is very weak. A clockwise eddy that used to emerge near west boundary in deeper layers in April seems to spread wider but an anti-clockwise one near south boundary almost disappears and turns to be a flow coming in from the east and going out from the west of south boundary at 5.0 m depth during this time. All eddies are combined and transformed to be a meander starting near the south boundary and ending at west boundary at 8.0 m depth.

Surface current is still strong and moderately complicated during the time of largest river discharge in September (Fig. 5b upper panel). The river outflow is strongest and density driven current could be clearly observed at the river mouth. A strong clockwise gyre appears at the north of west boundary and an anti-clockwise gyre arises at south boundary near the east coast. Over all flowing pattern has a trend of water coming in from west boundary and going out the area from south boundary. Two eddies near both open boundaries like those in April also emerge in deeper

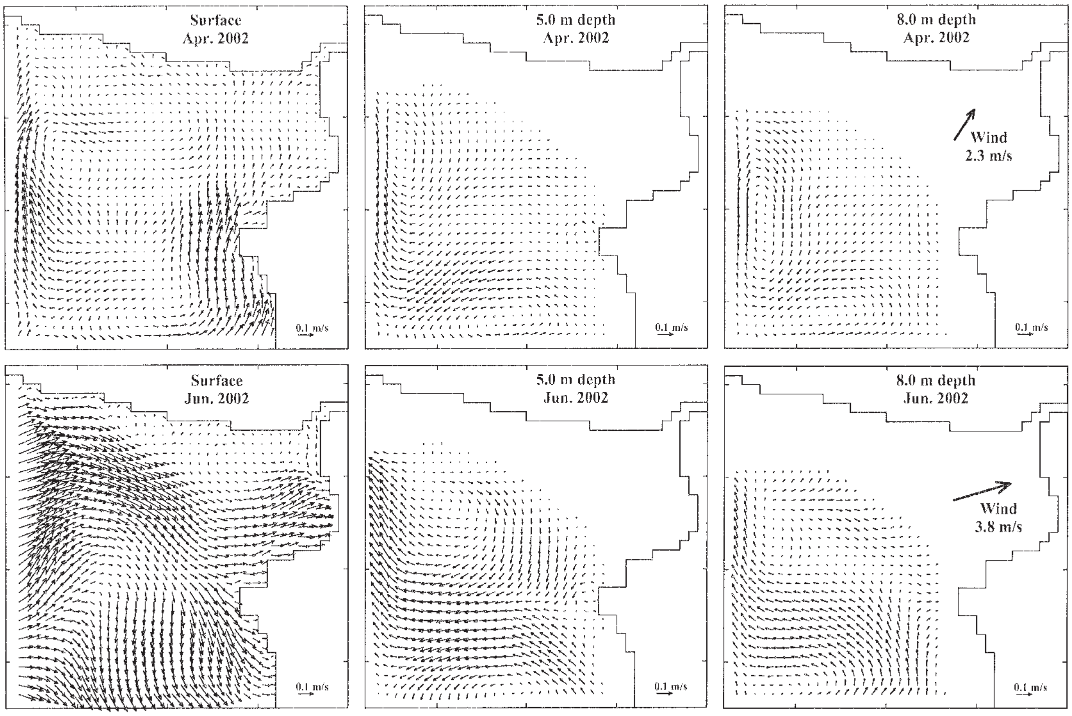


Fig. 5a. Calculated circulations at surface, 5.0 m depth, and 8.0 m depth in April and June 2002.

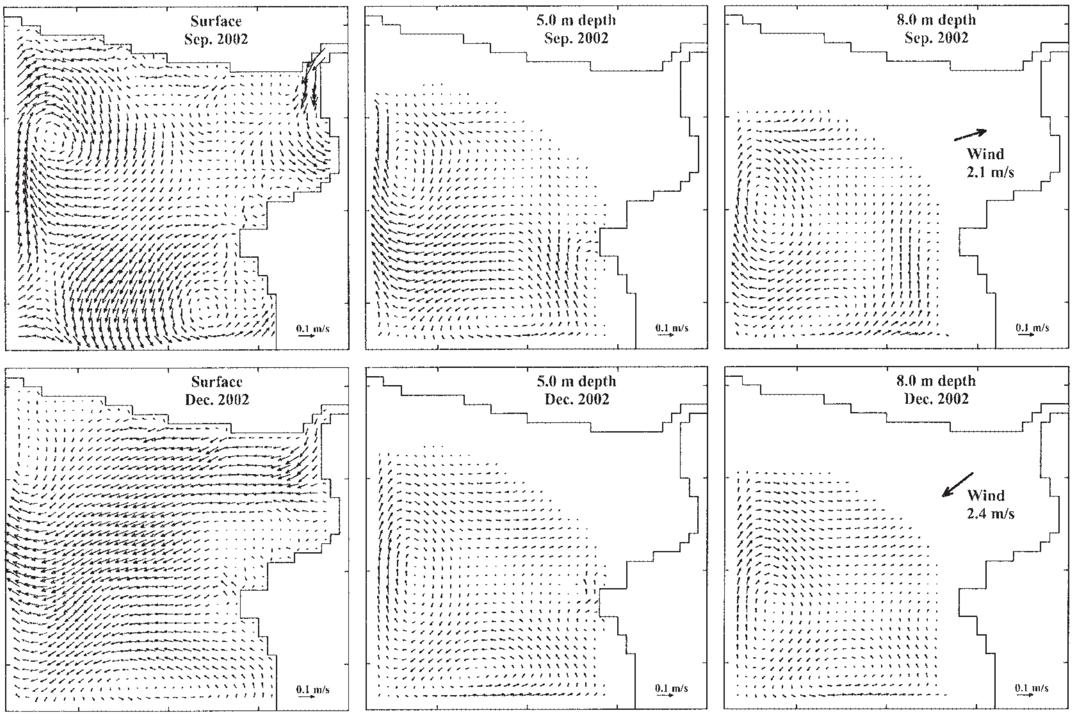


Fig. 5b. Same as Fig. 5a but for September and December 2002.

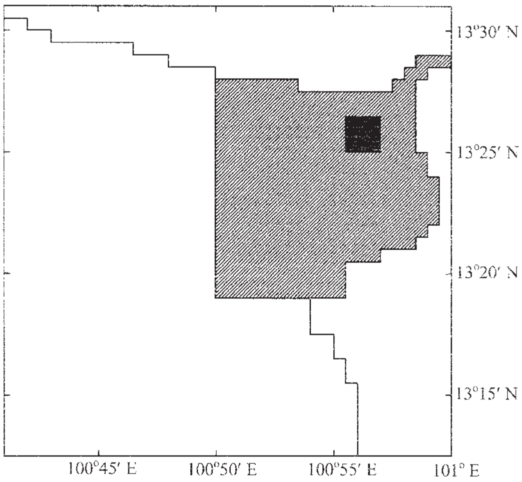


Fig. 6. Initial position of particles (solid rectangular area) and the boundary for the tracer experiment (screen area)

layers and near bottom water intrusion occurs along the north and east coasts. Current patterns at the sea surface in December (Fig. 5b lower panel) have a trend to flow seaward from the river mouth and move out through the middle of west boundary following the northeast wind that occupies over the area during this time. Eddies still appear along the open boundaries but they are very much weaker than those in September. Current patterns in deeper layers are not so different from the previous season, that is, there are two eddies along both open boundaries and intrusion of near bottom water into the river mouth from mid-area. Occurrence of the intrusion of near bottom water in September is supposed to be a part of density driven current because fresh water discharge is very large during this time while that in December should be occurred from compensation process to the outflow surface water from the river mouth to the sea.

Although the calculated currents are quite strong especially near the open boundary, the tracer experiment is still reliable because we focus our attention to the near field of river mouth shown Fig. 6 where the effect of currents near the open boundaries is very small.

## 4. Passive tracer experiment

We also apply POM for a material transport study in terms of the passive tracer experiment using Euler-Largrange method (YANAGI, 1999 a). A passive tracer having no sinking speed is initially spread into the computed current field near the river mouth and then its spatial and temporal distributions are calculated. The position of tracer $X_{n+1}$ $(x^{n+1}, y^{n+1}, z^{n+1})$ at time $n+1$, which was $X_n$ $(x^n, y^n, z^n)$ at time $n$, can be calculated by the following equations:

$$X_{n+1}=X_n+V\Delta t+\frac{1}{2}(\nabla V)\ V\Delta t^2, \tag{1}$$

where $V$ denotes the three-dimensional velocity vector of residual flow, ($\Delta t$ is the time step, and $\nabla$ is horizontal gradient. The spherical coordinate is used for the horizontal spatial derivatives. Thus those terms in equation (1) are transformed according to equations (2) and (3) as following:

$$\frac{\partial}{\partial x}=\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}, \tag{2}$$

$$\frac{\partial}{\partial y}=\frac{1}{a}\frac{\partial}{\partial\varphi}, \tag{3}$$

where $a$ is average radius of the Earth ($6.37\times 10^6$m) ;$\varphi$ and $\lambda$ are latitude and longitude, respectively.

A tracer module is added in the internal mode of POM and solved at the same time of the circulation and steps of the model operation are also the same as that of the circulation model. After all forces have been added and the circulation reaches a quasi-steady state about on 30 days, the tracers of 3,600 particles are spread at the sea surface near the river mouth (black square in Fig. 6) and then their movements are tracked until they all move out of a bounded area (screened area in Fig.6) or the computational time is over on 60 days. It should be noted here that computational boundary of the tracer experiment is smaller than that of the circulation as shown in Fig. 6. The reason is that we intend to compare our results with those from the previous study by BURANAPRATHEPRAT *et al.* (2002); therefore, the experimental area is set to close to the area in that study for equality in comparison. Residence time of the tracers will be derived from temporal change in their remaining number in the study area.

In order to find out the seasonal variation in average residence time of tracers in the area, a technique described by TAKEOKA (1984) and YANAGI (1999a), which has been applied in the studies of TAKEOKA and HASHIMOTO (1988), BALOTRO *et al.* (2002), and BALOTRO *et al.* (2003), is also applied in this study. We will investigate how the study area responses to the instantaneous input provided in the area in terms of the remnant function ($r(t)$), which is shown below.

$$r(t) = R(t)/R(0), \quad (4)$$

where $R(t)$ and $R(0)$ are the total number of tracers existing in the study area at any given time, and that in the initial time, respectively. Then the average residence time of the tracer ($\tau_r$) can be calculated by time integrating the results of the remnant function. That is

$$\tau_r = \int_0^\infty r(t)\,dt. \quad (5)$$

Seasonal variations in tracer distribution after spreading for 3 days, 5 days and 10 days are illustrated in Fig. 7 in order to see enough snapshots of their movement in the estuary. In April, the tracers are little dispersed and shift to the west of the river mouth on 3 days that they also remain around there by closer to the northern coast on 5 days. Most of them still last near the river mouth but some row in east-west along the north coast from the river mouth to west boundary on 10 days. Different scenes of the distribution are observed in June which is the transition period from dry to wet seasons. The particles move southwestward with a little spreading from the river mouth to mid-area from 3 days to 5 days. Instead of accumulation in a small area like in April, most of them still remain but are spreaded widely in almost entire the area on 10 days. Large river discharge in September makes the tracers widely disseminate and drives them out of the estuary very rapidly. Therefore, the distribution on 3 days in the central area looks not so thick because some particles have been moved out through the sea boundaries already. They are also spread widely but not many of them are still left inside the area on 5 days; however, rare numbers could be observed at the west of northern coast on 10 days. Particles are lined up in north-south in the mid-area on 3 days after releasing in December. Lower parts of this particle stripe are transported out through west boundary on 5 days and only small numbers with a few patches of them still suspend in the west of the river mouth vicinity on 10 days.

Time series plots of the remnant functions and calculated residence times of the tracers derived from equations (4) and (5) are illustrated in Fig. 8. Residence times are 29.1 days, 20.8 days, 6.0 days and 10.8 days in April, June, September and December, respectively. Longest residence time in April (29.1 days) occurs because of accumulation of the tracer with little spreading at the north coast (Fig. 7) of the estuary for a long time. The remnant function curve in April also shows that all particles still remain in the area until 17 days and then move out very slowly with about 3,000 particles left in the area at the end of calculation. In June, particles are dispersed widely and gradually transported out of the area starting from 5 days resulting in continually reduction in rate of the remnant functions and turns its residence time (20.8 days) to be the second order after that in April. Unlike the two previous seasons, residence time of the tracer is very short in September (6.0 days) because all particles are flooded out very rapidly by large river discharge. This phenomenon agrees to sharply reduction in the remnant function rate of change (Fig. 8) and the value becomes zero just on 15 days. However, although its rate of change reduces very fast at first, the remnant function in December still maintains itself in a narrow range from 0.2 to 0.4 from 5 days until the end of computation. This is the reason why the residence time in this season (10.8 days) is longer than that in September but shorter than those in April and June.

## 5. Discussions

Influences of wind, tide, and river discharge on circulation in the Bangpakong estuary vary in spatial and temporal scale. Seasonal variations in surface circulations (Fig. 5a and 5b) are mostly affected by wind and river discharge while influence of tide could be observed in


Fig. 7. Seasonal variation in predicted tracer distribution after 3 days, 5 days and 10 days.

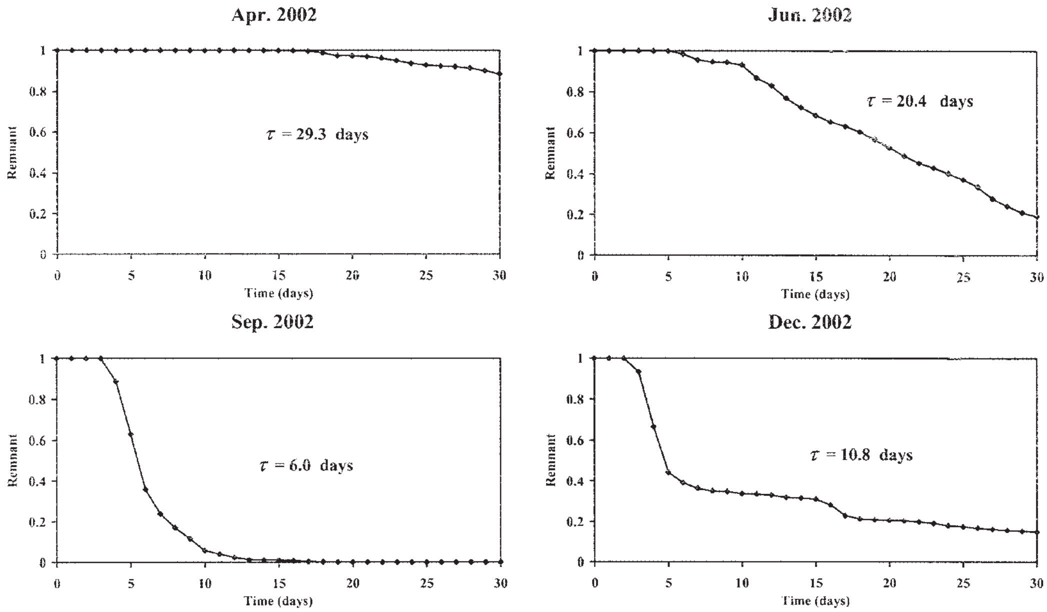


Fig. 8. Seasonal variations in the remnant function and average residence time of tracer.

entire water column. Surface current is quite strong but not so complicated when wind speed has strong power over other forces such as the condition in June. On the other hand, when there is not a force strong enough to govern the entire area, the current patterns would be complicated due to the interaction of all influences such as those in April, September and December. Permanent eddies, a clockwise and an anti-clockwise along west and south boundaries, respectively, in deeper layers are supposed to be generated by tide which is not changed seasonally. These results agree well with the calculated residual current driven by tide and wind in the study of BURANAPRATHEPRAT *et al.* (2003) which shows that the current patterns around that area do not quite change seasonally.

Influences of wind and river discharge are also observed in deeper layers when their influences are relatively strong. In June, for example, the stronger and wider clockwise eddy and the incomplete anti-clockwise one near south boundary at 5.0 m depth, and also transforming from eddies to a meander at 8.0 m depth are supposed to be caused by strong wind during that time. On the other hand, inflows of near bottom water from the mid-area to the river mouth in September suggest the occurrence of density-driven current because the river discharge is very large during that time. Alternative directions to the surface circulations of near bottom flow when the discharges are small may arise because of compensation process.

Interaction between circulation (Fig. 5a and 5b), material distribution (Fig. 7), and its residence time is discussed.It is quite clear that seasonal variations in wind driven circulation and river discharge have influence to the material distribution and also residence time. Longest residence time of the tracer in April (29.3 days) is controlled by moderate southwest winds which generate landward current to the river mouth at the same time of low river discharges. Therefore, particles will be forced to remain near the river mouth for a long time. In case of June although wind directions are also almost from the southwest, the residence time (20.4 days) becomes shorter than that in April because the discharge during this time is twelve-times larger (10 $m^3/s$ and 120 $m^3/s$ in April and June, respectively) and wind speed is stronger (2.3 m/s and 3.8 m/s in April and June, respectively). Instead of keeping particles inside the area, strong wind driven current will disperse

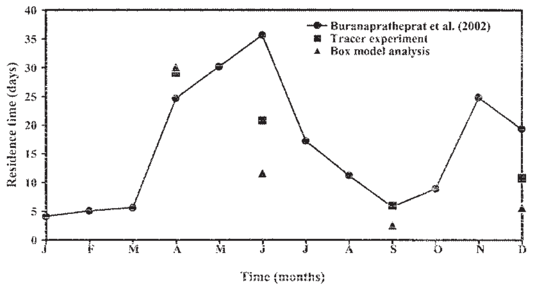


Fig. 9. Comparison of calculated residence times from the tracer experiment (solid rectangular) and box model analysis (solid triangle) with the results from the study of BURANAPRATHEPRAT *et al.*, (2002) (solid circle and solid line).

them widely in a short period (Fig. 7). Consequently, there is more opportunity that the particles are not so difficult to be conveyed by current out of the estuary.

The residence time of material is relatively very short in September (6.0 days) because the river discharge is extremely large even though wind is landward to the river mouth at that time, as a result the particles are flooded out in a very short time. In December, although the river discharge is very small (35 $m^3/s$) but the wind direction is seaward, the residence time (10.8 days) is therefore longer than that in September but shorter than those in April and June. This phenomenon confirms that the river discharge and wind speed play a significant role in controlling residence time of materials in the estuary. The influence of tide is not illustrated but should be noted here. The results of model operation with tidal force suggest the importance of tide that helps the material to move out of the estuary in a short time comparing with the operation without it.

Results from the tracer experiment are compared with those derived from a simple box model based on the mass balance of salt using the same salinity and river discharge data, and from the study of BURANAPRATHEPRAT *et al.* (2002) who also applied such a box model to investigate the residence time of fresh water in the same study area. Boundary for the box model analysis is assigned in the same way as that used in the previous study for equality in comparison. Please see more details of box model calculation in GORDON *et al.* (1996), YANAGI (1999b) or BURANAPRATHEPRAT *et al.* (2002). All the results are plotted and illustrated in Fig. 9. Results of box model analysis from this study which are 30.1 days, 11.7 days, 2.6 days and 5.7 days in April, June, September and December, respectively, indicate the same trend of seasonal variation in residence time to those from the tracer experiment. This suggests that the residence time of material based on calculated circulation with the use of Euler-Largrange method can reproduce the results derived from the mass balance of salt. However, the results in every seasons from this study also have the same trend as those from the previous study except that in June. In this study, the longest value appears in April while that of the previous study emerges in June. This suggests a possibility of year-to-year variations of river discharge and/or wind. If discharge is smaller and wind speed is weaker in June of some year which is the transition period from dry to wet seasons, the residence time of material can become very long in the same way as that in the previous study. It should be noted here that the distinct characteristics of computed material and fresh water such as diffusion and dispersion properties might result in the difference of calculated residence times from the tracer experiment and the box model analysis.

Importance of the transition period when DIN (dissolved inorganic nitrogen) and chlorophyll-*a* concentration are high, which was discussed in BURANAPRATHEPRAT *et al.* (2002), still remains because not only residence time but also the nutrient loading has to be considered. The rough multiplication of calculated residence times from this study (29.1 days, 20.8 days, 6.0 days and 10.8 days in April, June, September and December, respectively) and DIN load estimated from the results presented in BURANAPRATHEPRAT *et al.* (2002) (10 tons/-month, 300 tons/month, 500 tons/month and 30 tons/month in dry season, transition period from dry to wet seasons, wet season and transition period from wet to dry seasons, respectively) also show highest concentrations of DIN during the transition period between dry and wet season. Therefore, the hypothesis that eutrophication in this estuary is promoted during this transition period is still reasonable.

This study has made us to understand clearer in physical processes in terms of water circulation and a material transport. However, we will also use an ecological model which considers not only physical processes but also biogeochemical processes to investigate the mechanism of eutrophication phenomenon in the Bangpakong estuary in the near future.

## 6. Conclusions

POM is applied for investigation the seasonal variations in 3-dimensional circulation and residence time of a tracer in the Bangpakong estuary employing observed salinity and temperature, average wind velocity, river discharge, and calculated tidal elevation as significant computational inputs. Wind driven current is predominant and its magnitude is large at the sea surface while tidal prevalence is observed throughout the water column. Influence of river discharges as an outflow and density driven current are also observed near the river mouth during wet season. The tracer experiment indicates that tide plays an important role to move material out of the estuary in a short time. However, seasonal variation in residence time mainly depends on variations in wind driven circulation and river discharge, that is, it is longest in April and shortest in September.

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