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Seasonal Variations in Circulation and Salinity Distributions in the Upper Gulf of Thailand: Modeling Approach

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Abstract : Seasonal variations in circulation and salinity distributions in the upper Gulf of Thailand are investigated by using a 2-D hydrodynamic model. The computed results of circulation are used as inputs in a simple model to calculate salinity distribution to verify the computed results with those of the observation from a previous study. The model succeeds to reproduce salinity distribution that confirms the reliability of computed circulation. During the southwest monsoon, a clockwise gyre is generated near the head of the Gulf with northward inflow and southward outflow in the southwest and the southeast of the upper Gulf, respectively. However, there is no complete gyre during the northeast monsoon, just flow along the coast from the east to the west, and then flow out of the Gulf at the southwest, consecutively. The results roughly inform the oceanographic condition regarding the occurrence of strong eutrophication in the eastern part of the upper Gulf during the southwest monsoon. More realistic 3-D hydrodynamic model and ecological model will be used to investigate the mechanism of this phenomenon in the future.

Key words : *Gulf of Thailand, wind-driven curent, seasonal variation, salinity distribution*

1. Introduction

The upper Gulf of Thailand (Fig. 1) is located in the tropical region at 13°N and 100°E. It is surrounded by land in the eastern, northern and western sides, and is open to the lower Gulf of Thailand via the southern border. It has an approximate area of 10^4 km^2 with the maximum depth of 40 m at the southeastern area. The area is under the two-monsoon wind system, the dry northeast (November to January) and the wet southwest monsoon (May to August). The northeast wind during the northeast monsoon brings cool and dry air from Siberia, while the west to southwest winds bring moist air from the Indian Ocean into the region (SOJISUPORN, 1994).

The upper Gulf is one of the significant economic areas for the Thai nation. Large-scale farming of the green mussel is largely confined to coastal areas in the upper region of the Gulf of Thailand, and the major mussel-producing provinces are all close to Bangkok where major markets are located (CHALERMWAT and LUTZ, 1989). Fisheries are also important in such a shallow area. Although overfishing has almost wiped out the high-priced fish species, the income from local fishery is still a major one. Furthermore, maritime activities are rapidly stimulated in present time because of industrial development. Therefore, many commercial ports are developed and located around the upper Gulf. However, tourism and recreation activity are also important for the nation income and cannot be overlooked.

Rapid country development and population growth have resulted in pollution problem and deterioration of the Gulf condition. Anyway, the most conspicuous and widespread pollution impact on the marine environment of the Gulf is perhaps eutrophication (CHONGPRASITH and SRINETH, 1998). And consequently, massive blooms of phytoplankton frequently occurred in the area, especially in the eastern side of the upper Gulf of Thailand (SOJISUPORN, 1994;

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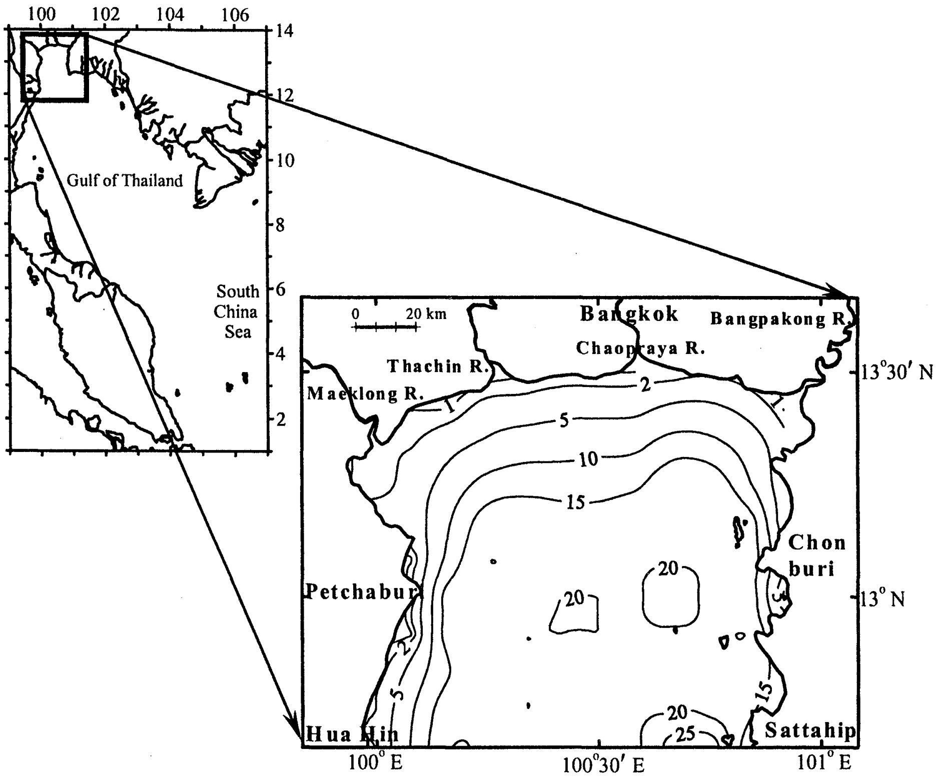

Fig. 1. The upper Gulf of Thailand. Contours show the depth in meters.

CHONGPRASITH and SRINETH, 1998). One of the major causes of phytoplankton bloom is from excessive nutrients and organic pollutants carried down by major rivers in the head of the upper Gulf, namely the Maeklong, the Thachin, the Chaopraya and the Bangpakong, located from the west to the east, respectively. However, the reason why blooming frequently appeared in the eastern part of the upper Gulf is still not understood well.

According to the importance and problems of the upper Gulf of Thailand, understanding in oceanographic condition becomes the vital key to access the ways to use it sustainedly. Many studies have been done (e.g. NEDECO, 1965; NEELASRI, 1981; SOJISUPORN and PUTIKIATIKAJORN, 1998) but their results of circulation are different depending on the methods and assumptions of the authors. Therefore we cannot clarify the oceanographic view of the area and still in doubt at present time. As for the seasonal variation of 3-D circulation in the whole area of the Gulf of Thailand, numerical experiment (YANAGI and TAKAO, 1998) is already conducted. However the information on the upper Gulf is limited because their mesh size is too large as 10 km.

Although direct measurement is the best way to get the oceanographic information, it consumes very much time and budget. With the hope to get the general information of seasonal variation of the circulation in this area, this is a try to investigate the circulation in the upper Gulf by using a 2-D hydrodynamic model. And, the results of circulation will be applied as inputs to calculate the seasonal salinity distributions, which will be compared with those of the observation from a previous study.

2. Numerical experiment

In order to find out the horizontal circulation of the upper Gulf of Thailand, a prognostic numerical model developed by BUNPAPONG *et al.* (1985), and BURANAPRATHEPRAT and BUNPAPONG (1998) is adopted. This model uses ADI (Alternating Direction Implicit) technique to solve the governing momentum and continuity equations shown as follows:

$$\frac{\partial u}{\partial t} - 2\Omega \sin \varphi \cdot v + gD\frac{\partial \eta}{\partial x} = T_{sx} - T_{bx}, \tag{1}$$

$$\frac{\partial v}{\partial t} - 2\Omega \sin \varphi \cdot u + gD\frac{\partial \eta}{\partial y} = T_{sy} - T_{by}, \tag{2}$$

and

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \eta}{\partial t} = 0, \tag{3}$$

where x and y are distance in east - west and north - south directions (m), respectively, u and v are transports per unit width (m^2/s) in x and y directions, respectively, η is water elevation (m), g is gravitational acceleration (9.8 m/s^2), D is averaged depth (m), t is time (s), Ω is angular velocity of the Earth rotation (7.29×10^{-5} rad/s), ϕ is latitude (radian), T_{sx} and T_{sy} are wind stress terms in x and y directions, respectively, and T_{bx} and T_{by} are bottom stress terms in x and y directions, respectively. The general forms of surface and bottom stress terms are presented in equations (4) and (5).

$$T_s = k_s \mid W \mid W, \tag{4}$$

$$T_b = k_b \mid V \mid V, \tag{5}$$

where k_s is wind stress coefficient (1.1×10^{-6}), and k_b is bottom stress coefficient (2.5×10^{-6}) (BUNPAPONG *et al.* 1985), W is wind velocity at 10 m above sea level (m/s), and V is water current vector (m/s). In the momentum equations (equations (1) and (2)), we neglect the terms of horizontal viscosity because they are considered to be very small in order of magnitude when comparing with other terms. The spherical coordinate is used with grid spacing 1 x 1 minute in latitude and longitude (about 1.7 km), respectively. Thus, the spatial derivative terms in equation (1) to (3) will be transform according to equation (6) and (7).

$$\frac{\partial}{\partial x} = \frac{1}{a \cos \varphi} \frac{\partial}{\partial \lambda} \tag{6}$$

and

$$\frac{\partial}{\partial y} = \frac{1}{a} \frac{\partial}{\partial \varphi}, \tag{7}$$

where a is average radius of the Earth (6.37×10^6 m), ϕ and λ are latitude and longitude (radians), respectively.

The mean depth from the navigation chart, and the 8-year (1990–1998) averaged wind field from ECMWF (European Center of Medium Range Weather Forecast) (Fig. 2) are employed as inputs in computation. The model is taken initially at rest or no-motion condition. Normal component of volume transport is specified as zero along the solid coastal boundary. At the sea boundary, water elevation at the east (Sattahip) and the west (Hua Hin) end points (Fig.1), calculated by using the harmonic analysis technique, are linearly interpolated to fill in all grids along the open boundary between them. The predominant tidal constituent from SOJISUPORN and PUTIKIATIKAJORN (1998) are used for the harmonic calculation of tidal elevation, whose values are shown in Table 1. The monthly mean river discharges from the Hydrographic Department, and BOONPHAKDEE *et al.* (1999) are conditions at the river boundary. The model is operated with time step of 1800s, and running time for 30 days.

3. Seasonal circulation

The results of seasonal circulation due to the monsoon winds plus the tide-induced residual current are presented in Fig. 3. Currents have averaged magnitude of 0.44, 0.40, 0.70, and 0.36 cm/s in the northeast, the transition from the northeast to the southwest (NE-SW), the southwest, and the transition from the southwest to the northeast monsoon (SW-NE), respectively. During the northeast monsoon, circulation has trend to flow in counter-clockwise direction along the coastline from the east to the head of the Gulf, and then flows to the west, respectively. This current continues flowing southward along the west coast, and finally runs out of the Gulf in the southwestern part. The counter-clockwise flow presented in the northeast monsoon becomes weaker in the NE-SW transition period. A clockwise gyre appears at the northwestern

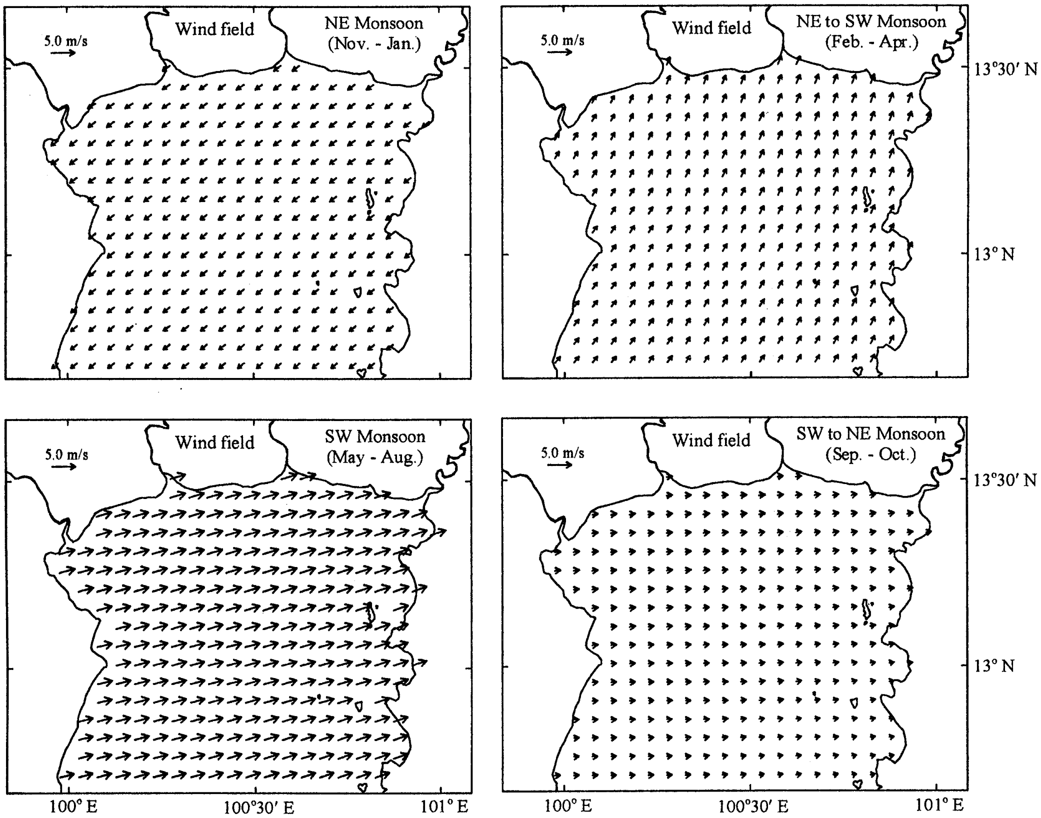

Fig. 2. Seasonal wind fields over the upper Gulf of Thailand

Table 1 Major harmonic constituents used to calculate the tidal elevation at the sea boundary.

Tidal Constituent	Hua Hin		Sattahip	
	Amplitude(m)	Phase(degree)	Amplitude(m)	Phase(degree)
K_1	0.609	167	0.587	162
O_1	0.396	117	0.393	112
M_2	0.327	140	0.261	121
S_2	0.158	213	0.123	192

part of the Gulf. Strong northward currents can be observed along the eastern coast in this season, which are the same as those in the previous season.

Circulation during the southwest monsoon dramatically changes from that during the northeast monsoon. The counter-clockwise flow vanishes in this season, but a big strong clockwise gyre appears near the head of the Gulf. The current flowing into the Gulf in the southwestern part separates into two directions, the northward along the west coast, and the northeastward to the central of the lower half of the Gulf. The northward flow along the chain of eastern islands is still observed but the magnitude is weaker than those in the two previous seasons. Strongest currents from main rives are perceived during the SW-NE transition period because of high river discharge in this period. However, over all current in the Gulf is weaker and more complicate than other time. The clockwise gyre disappears and retreats as a weak clockwise flow along the coast in the northwestern area.

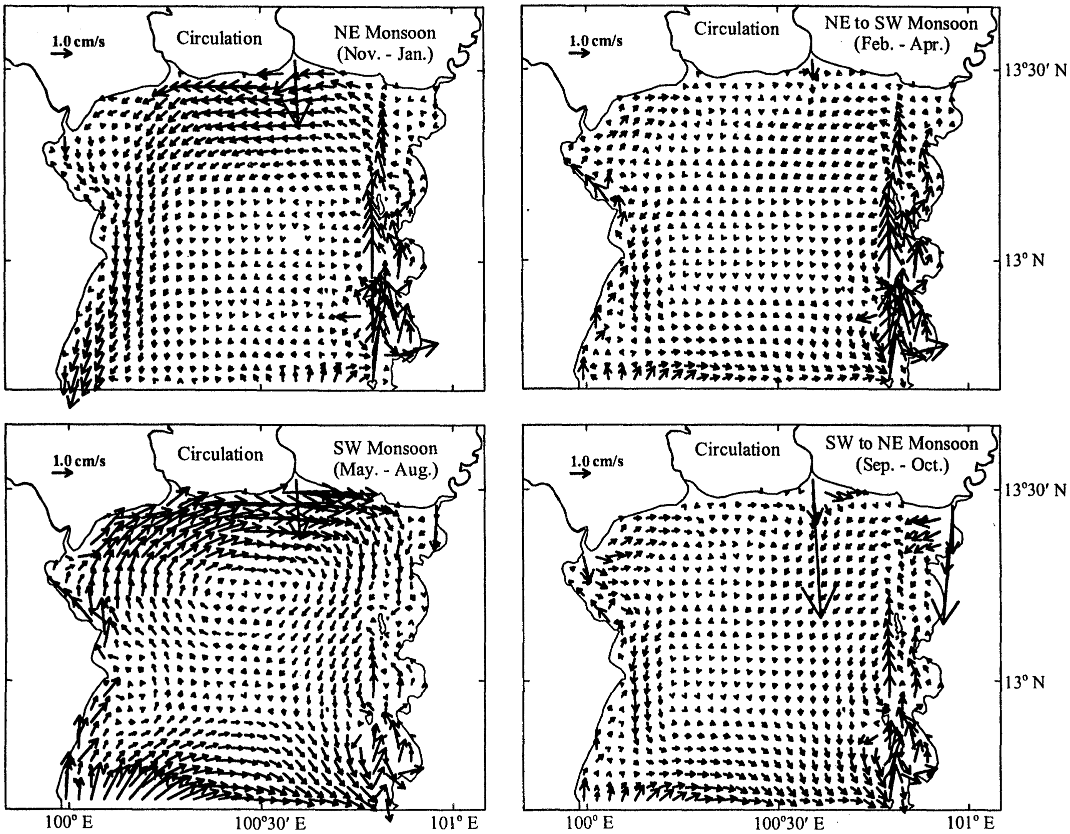

Fig. 3. Calculated seasonal circulation in the upper Gulf of Thailand.

3. Salinity distribution experiment

In this study, because of the lack of measured current data to be verified with the computed results, we have to try to simulate the seasonal salinity distribution in the upper Gulf of Thailand by using computed circulation as input. And the results will be compared with the picture of the seasonal distribution of sea surface salinity in the same area (Fig. 4), which was intensively measured and presented by NEDECO (1965). The objective of the study is to examine if the computed results of seasonal circulation can reproduce the salinity distribution in the same way as those from the measurement. Vertical stratification is developed only in the central and southern parts of the Gulf of Thailand throughout the year and the water column is vertically mixed near the head of the Gulf because $\log_{10}(H/U^3)$ is smaller than 2.5 (H; water depth in meters, U; tidal current amplitude in m/sec) there (YANAGI *et al.*, 2001).

The governing equation to calculate salinity distribution is shown below:

$$\frac{\partial s}{\partial t}+u\frac{\partial s}{\partial x}+v\frac{\partial s}{\partial y} = K_h\left(\frac{\partial^2 s}{\partial x^2}+\frac{\partial^2 s}{\partial y^2}\right), \tag{8}$$

where s is salinity (psu), and K_h is the horizontal diffusivity (m^2/s). The detail how to consider the value of K_h will be described later.

We use the spatial coordinate in the same way as that in the circulation model, with the central scheme of the finite difference technique. Time step is 3600s with running time of 1,200 days because the solutions become stable at the day of 1,100. Salinity at the river boundaries are fixed and set as zero, while those at the sea boundary are assumed to depend on the observed results in Fig.4. Values of K_h are adjusted seasonally depending on the computed results of salinity. If the K_h is too small, some errors will be generated in the results. Thus, we

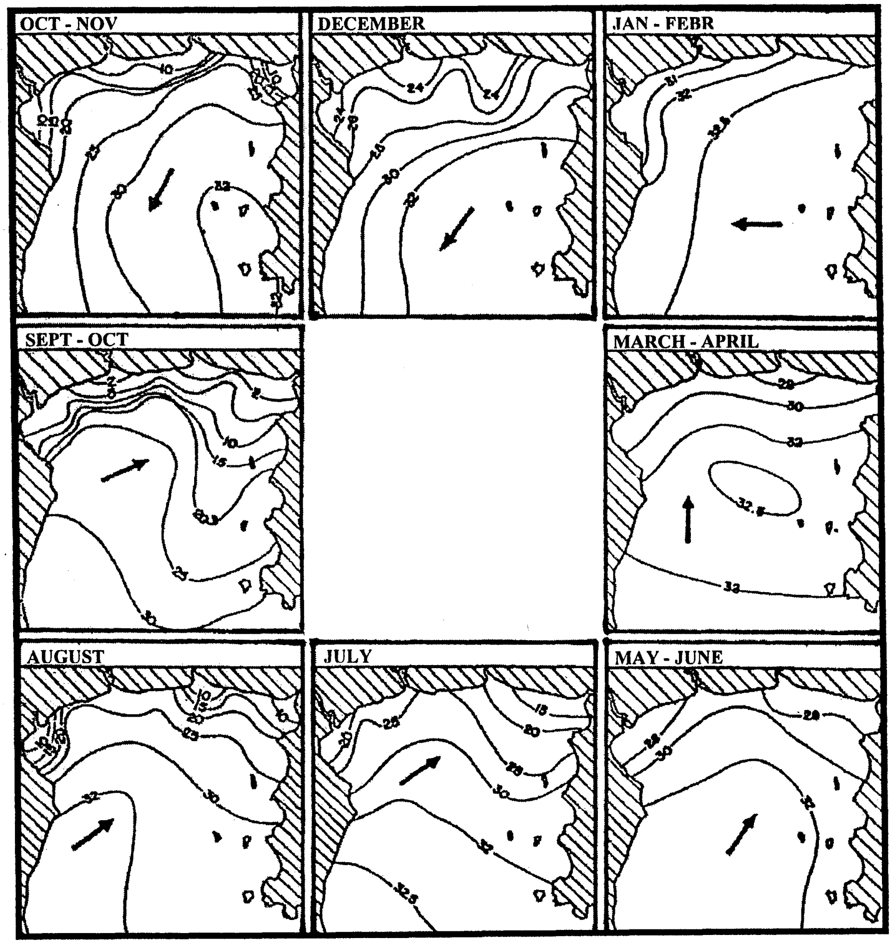

Fig. 4. Seasonal variations in salinity distribution in the upper Gulf of Thailand. Arrows show the wind direction(NEDECO, 1965).

Table 2 The list of some parameters used as inputs in computation of salinity distribution

Seasons	Initial sal.(psu.)	Boundary sal.(psu.)	K_h(m^2/s)
Northeast	31.0	33.0	1.5
Northeast to Southwest	29.0	32.0	1.5
Southwest	25.0	32.5	30.0
Southwest to Northeast	20.0	30.0	15.0

choose the minimum K_h value in each operation that can maintain the reliable outputs. The values of salinity for initial and boundary conditions, and K_h are summarized and presented in Table 2.

The computed results of seasonal distribution of salinity in the upper Gulf of Thailand are shown in Fig.5. Salinity is quite high during the northeast monsoon with tendency of low salinity in the west coast. Anyway, low salinity also appears in the east coast just near the Bangpakong river mouth. In the NE-SW period, a plume of low salinity water occurs in the northwestern area, while higher salinity arises as the background in the entire area. A meander of low salinity appears from the mid-west

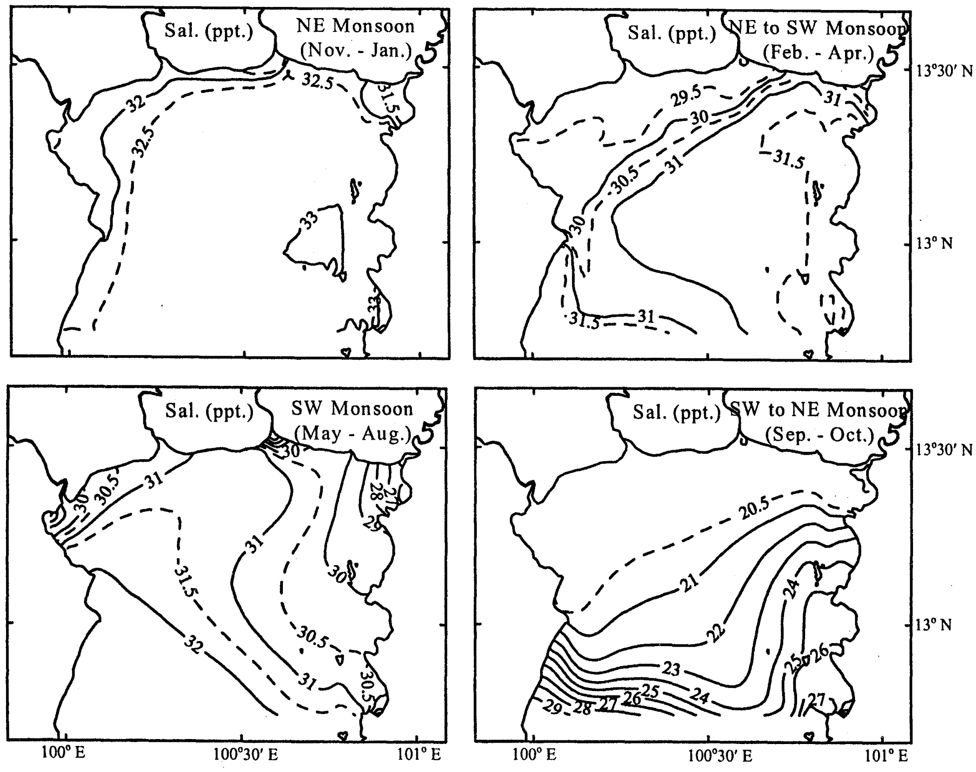

Fig. 5. Computed salinity distribution in the upper Gulf of Thailand.

coast to the central of the southern end. However, the salinity distribution is dramatically shifted from those in the two previous seasons during the southwest monsoon. Relatively high and low salinity presents in the west and the east coasts, respectively. Lowest salinity can be observed near the Bangpakong river mouth, and the values are gradually high along the east coast from this area to the sea boundary. The contours illustrate that high salinity from the west coast penetrates to the east near the mid-north coast, while low salinity percolates from the east to the west in the mid-Gulf. During the SW-NE transition period, except the sea boundary region, salinity is quite low in the remaining area. High salinity water from the south advances into the Gulf along the east coast, while it retreats because of the low salinity water mass in the southwestern site. As a result, salinity in the upper half of the Gulf is lower in the west than that in the east.

4. Discussions

Unfortunately, we have no raw numerical data from the previous studies to be correlated mathematically with the computed results of salinity distribution. Therefore, we can just compare the figures of the measured from a previous study with those of the computed by this study. However, it is quite clear that the computed results of salinity distribution (Fig. 5) coincide with those of the measured (Fig. 4), although the former represents the depth-averaged salinity while the latter are the values at the sea surface. Good comparisons are observed during the mid-northeast and the mid-southwest monsoons. Because the patterns of wind field at these times are quite stable, which can generate the unique and stable patterns of circulation and salinity distributions. On the contrary, it is quite hard to reproduce the observed patterns during the monsoon transition because of the year-to-year variation in the time of monsoon change.

From the success to reproduce the salinity distributions, we can refer them back to the patterns of circulation. The figures of salinity distribution (Fig. 5) and seasonal circulation (Fig. 3) illustrate the closed gyre occurring only in the southwest monsoon. While in the northeast monsoon, the closed gyre cannot be generated. It may be from the interaction between wind direction and coastal morphology. The main balance in the momentum equations of (1) and (2) is between the surface and bottom stresses because the horizontal scale of the upper Gulf (about 100 km) is much smaller than the Rossby's deformation length λ of 370 km ($\lambda=(gH)^{1/2}/f$; $g=9.8$ m/s^2, $H=15$m and $f=3.3\times10^{-5}$ rad/s). Strong west and southwest wind during the southwest monsoon will push water in the shallow region along the north coast to move strong and fast to the east. And when the current batters the east coast, it will reflect back to the west along the central line separating the northern and the southern Gulf due to the horizontal geometry, generating a closed clockwise circulation. However, during the northeast monsoon, strong northeast wind just induced water movement consecutively along the coast from the north to the west, and then flows out of the Gulf at the southwestern boundary. This counter-clockwise flow is compensated by the northward inflow of seawater along the east coast. Therefore, the closed gyre cannot occur, just flows along the coast from east to north, to west, and then flows out at the southwest, respectively.

The frequent occurrence of phytoplankton bloom in the northeastern Gulf should be discussed here as well. This phenomenon can be mentioned to the eutrophic condition from high nutrient accumulation in the area. The study of NRCT-JSPS (1998) pointed out the significant source of nutrient from the Bangpakong River. Anyway, the results of circulation and salinity distribution suggest the oceanographic condition promoting the condition other than loading from the Bangpakong River. It is obvious that nutrient loads from four main rivers in the upper Gulf (Fig. 1) are very high depending on large freshwater discharge in wet season, which is the time of the southwest monsoon. The west and southwest wind prevailing over the upper Gulf (> 6 months per year: ECMWF data) will generate the clockwise gyre near the head of the Gulf (Fig. 3), which let discharges from the river mouths flow from the west to the east along the north coast. As we can see in the salinity distribution during the southwest monsoon (Fig. 5) that indicates the influence of discharge from the Chaopraya river over the area near the Bangpakong river mouth and the eastern coast of the Gulf. Not only freshwater but also contaminants such as nutrients are also driven to the east. Therefore, this terminal area will suffer from the nutrient transport and then the eutrophic condition is promoted for long period of the year.

However, the above reason for the eutrophic condition is just a possible assumption according to the results from this study. We will have to investigate the details of mechanism by using 3-D hydrodynamic model and ecosystem model in the near future. The 3-D model can let us know more realistic oceanographic condition because it include effects not only from wind, tide, and river discharge but also from horizontal density difference (density driven current), and sea surface height. And, we will use the ecosystem model, which considers the biological factors to investigate the mechanism of the phenomenon.

5. Conclusions

The seasonal variations in circulation and salinity distributions in the upper Gulf of Thailand are investigated by using a 2-D hydrodynamic model. Comparable results of salinity distributions from the computation and those from the observation confirm the reliability of computed circulation. During the southwest monsoon, a clockwise gyre is generated near the head of the Gulf with northward inflow and southward outflow in the southwest and the southeast of the upper Gulf, respectively. However, there is no closed gyre during the northeast monsoon, just flows along the coast from east to west, and then flows out of the Gulf at the southwest, consecutively.

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