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# Seasonal variation of sea surface current in the Gulf of Thailand

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**Abstract**—In this study, the seasonal variations in the surface water currents within the Gulf of Thailand were revealed through the use of (i) temperature and salinity data derived from the world ocean database, (ii) the monthly dynamic heights anomaly (DHA) from TOPEX/Poseidon and (iii) the ERS-2 altimetry data, during 1995–2001. The mean dynamic height (MDH) and mean geostrophic current were derived from the climatological temperature and salinity data, while the DHA data was derived from the MDH and their geostrophic currents. The mean geostrophic current showed a strong southwestward flow of the South China Sea water along the gulf entrance. Counterclockwise eddies in the inner gulf and the western side of the gulf entrance were associated with upwelling in the area. Seasonal geostrophic currents showed a basin-wide counterclockwise circulation during the southwest monsoon season and a clockwise circulation during the northeast monsoon season. Upwelling was enhanced during the southwest monsoon season. The circulation patterns varied seasonally probably due to the variation in wind regimes. Finally, the congregation, spawning, and migration routes of the short-bodied mackerel were found to conform to the upwelling and surface circulation in the gulf.

**Key words:** sea surface dynamic height, geostrophic current, upwelling/downwelling, Gulf of Thailand

## Introduction

The Gulf of Thailand (GOT) is a shallow semi-enclosed bay on the continental shelf of Asia, bordered by Malaysia, Thailand, Cambodia and Vietnam on the western, northern and eastern sides, respectively, leaving the gulf connecting to the South China Sea via the southern side (Fig. 1). The gulf has a roughly rectangular shape, with a width of 400 km and a length of 720 km, and aligns itself along a NW-SE direction. The water is deeper in the central gulf but attains a maximum depth of only about 80 m. The shallower upper Gulf of Thailand (UGOT in Fig. 1), formerly called Bangkok bight, is about 100×100 km in size and is connected to the gulf at the northern most end.

The gulf serves local people in various ways, such as fishing grounds, important shipping routes for foreign trade, sites for oil and gas exploration, recreation areas along the coasts, and an illegal dumping ground for domestic, agricultural and industrial wastes. Too much exploitation in the gulf has lead to dwindling living resources, deteriorating water quality and it is also prone to oil spill accidents and ship freight and ballast tank discharges, etc.

The ocean current is a very important physical parameter that controls the water exchange and dispersion of organic and inorganic substances in the water body. A fuller characterization of the prevalent currents would help in allowing a better understanding of the behaviors of living organisms and allow for better management of the natural resources in the Gulf. Unfortunately, the ocean currents in the GOT have been poorly studied and remain somewhat largely unknown. In 1961, the circulation patterns in the Gulf were first proposed by the Hydrographic Department of the Royal Thai Navy (Fig. 2 unpublished). The patterns were probably based on local knowledge and a diagnostic model of flow in the Gulf of Thailand (Neelasri, 1978).

Earlier field surveys together with tidal records and tidal model results have pointed out a dominant role of tidal currents in the GOT (Pukasab and Pochanasomburana, 1957; Wyrtki, 1961; Hydrographic Department, 1968; Robinson, 1974; Hydrographic Department, 1995; Choi et al., 1996; Yanagi et al., 1997; Buranpratheprat and Bunpapong, 1998; Yanagi and Takao, 1998a). However, in contrast, Yanagi and Takao (1998b), after studying the circulation in the GOT using a 3-dimensional numerical model, concluded that tidal currents contributed very little in terms of the net circulation and the exchange of water mass between the Gulf and the South China Sea. Field data and numerical model results indicated that the predominant monsoonal winds caused eddies, mixing and the exchange of water mass in the Gulf

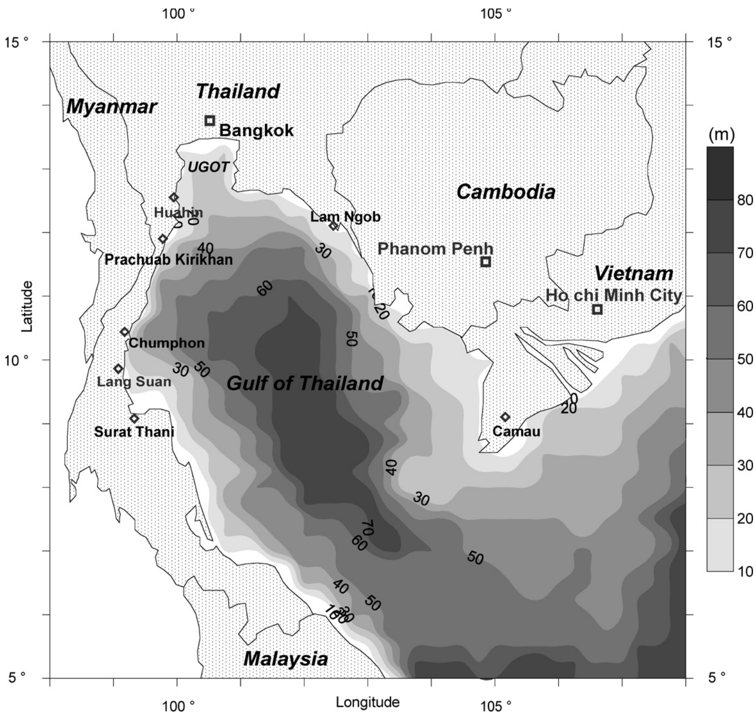



**Fig. 1.** Geography of the Gulf of Thailand.

(Siripong, 1984; Buranpratheprat and Bunpapong, 1998; Robinson, 1974; Yanagi and Takao, 1998a). Moreover, using sea surface temperature and salinity data from oceanographic buoys during 1994, together with tide and wind regime data, to derive the 3-D circulation in the GOT, very complex and varied weekly circulation patterns in the gulf were revealed (Lowwittayakorn, 1998). However, such predicted temporal and spatial variations of sea surface circulation within the GOT have not yet been confirmed.

With the use of altimetry data, the basin-wide temporal surface circulation in the marginal seas can be studied. For example, Morimoto et al. (2000) studied the temporal and spatial variations of sea surface circulation in the South China Sea through the use of TOPEX/POSEIDON altimetry data and found the response of surface circulation to Asian monsoon wind. Although a large tidal error in altimetry data in many parts of the Asian marginal seas has been found, the tidal error for the GOT was found to be rather small (Morimoto, 2009).

Upwelling in oceans is important because, for example, in nutrient recycling where benthic organic and mineral components are redistributed to, and made available for the surface ecosystem, so high fish productivity is usually associated with the upwelling area (Wooster, 1981). For example, the coast of Peru is a well-known coastal upwelling area caused by the trade winds (Ancieta, 1981). Upwelling/downwelling can occur in an area off the coast where the eddy current or surface divergence caused by current shear takes place. Based on Wyrtki's (1961) report, Cushing (1969) stated that upwelling occurred on the west coast in the GOT in August, and on the northeast coast in October and January, whilst a slight upwelling occurred all year round at 12°N and 101°W. Michida et al. (2006) found a good correlation between the surface divergence/upwelling with chlorophyll-a levels in the upper GOT. Further to this, Buranapratheprat et al. (2008) found that coastal upwelling and surface chlorophyll-*a* in the upper GOT were related to the monsoonal wind in the area.

In this study we try to reveal the seasonal variation of sea surface currents in the GOT through the use of the archived climatic and altimetry data and relate the circulation to the possible upwelling/downwelling of water mass in the area.

## Method

Sea surface circulation, specifically the geostrophic currents, can be derived from the dynamic topography of the sea surface. Satellite altimetry data gives useful information in terms of the dynamic topography with high spatial and temporal resolutions. Although the temporal fluctuation component of the dynamic topography can be calculated from the altimetry data, mean dynamic topography during the data period cannot be derived from the altimetry data because of a large error of geoid. For this study, the long-term MDH, calculated by dynamic calculations using the climatic mean water temperature and salinity of the World Ocean Data (http://www.nodc.noaa.gov/), is regarded as the mean dynamic topography. Since the temperature and salinity data

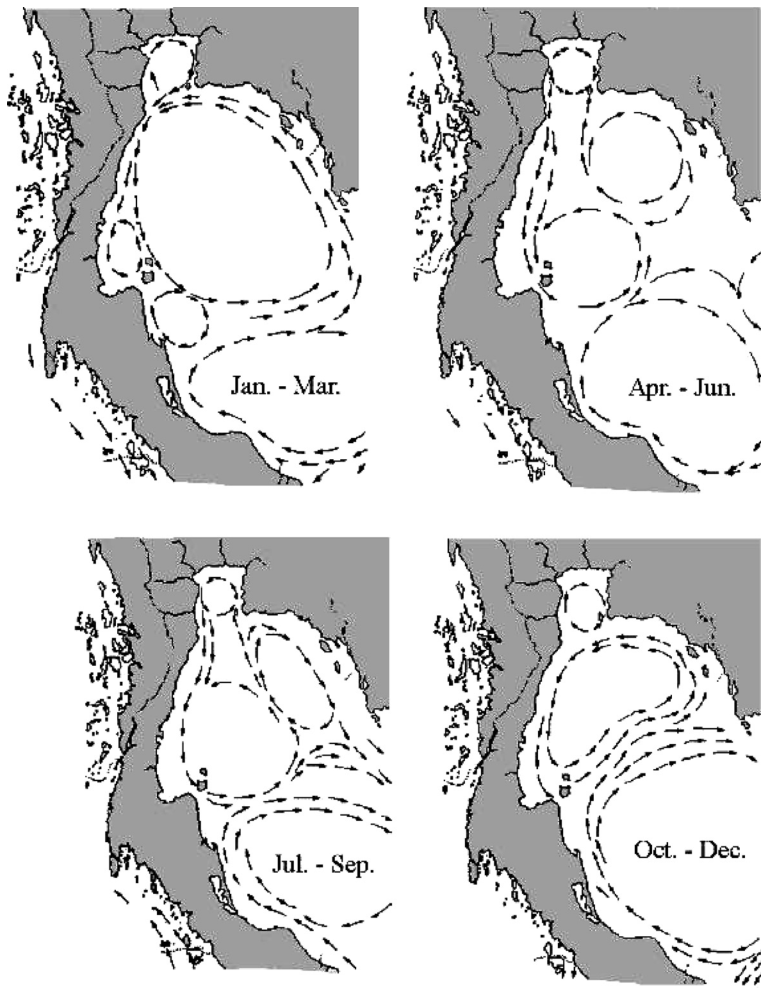



**Fig. 2.** Seasonal circulation in the Gulf of Thailand, as suggested by the Hydrographic Department in 1961 (unpublished).

were not equally spaced horizontally and vertically, they must be interpolated into equally-spaced grid points. The study area is covered by 5°–14°N and 99°–108°E, with a horizontal grid spacing of 0.25° zonally and meridonally. The data were also interpolated vertically with a depth spacing of 10 m. We used an exponential function for interpolation as follows:

$$\xi(x, z) = \frac{\sum_{i,k} W(x, r_i, z, r_k)\tau(r_i, r_k)}{\sum_{i,k} W(x, r_i, z, r_k)}$$

$$W(x, r_i, z, r_k) = \exp\left\{-\frac{(r_i - x)^2}{L^2} - \frac{(r_k - z)^2}{D^2}\right\}$$

where $\xi(x, z)$ denotes the interpolated value, $x$, $z$ the positions of horizontal and vertical interpolations, respectively, $r_i$, $r_k$ the horizontal and vertical positions of the original data, respectively, $\tau(r_i, r_k)$ the temperature or salinity data, $L$ the horizontal decorrelation scale which was taken to be 0.5° (about 55.6 km) for both N–S and E–W directions, and $D$ the vertical decorrelation scale which was taken to be 10 m. Water depth at each grid point must be specified and we used 90 m as the maximum water depth in the study area because the maximum depth in the gulf is less than 90 m (Fig. 1).

The next step was to compute the MDH from the interpolated temperature and salinity data, using the dynamic calculation (Pond and Pickard, 1983). Normally the dynamic height in the deep ocean is computed from the depth of no motion, usually taken at 1,000 or 1,500 m below the sea surface. But since the water depth in the GOT is much shallower than this (≤90 m), the dynamic height was computed from the surface down to the bottom only. The mean geostrophic current was computed at the middle of the square with the MDHs at each corner. The depth of no motion for the square was the shallowest depth of the four corner points. Thus, the depth of no motion changed from square to square. The mean geostrophic current was computed using the following equations;

$$f v_m = g\left(\frac{\partial h_m}{\partial x}\right), \quad f u_m = -g\left(\frac{\partial h_m}{\partial y}\right)$$

where $f$ denote the Coriolis parameter ($=2\Omega \sin(\phi)$ where $\Omega=7.29*10^{-5}\,s^{-1}$ and $\phi$ the latitude), $v$ meridonal current speed, $u$ zonal current speed, $\partial h_m$ difference in mean dynamic height over $\partial x$, $\partial y$ grid spacings (0.25°).

Delayed time products of the corrected sea surface heights (CorSSH) data for TOPEX/Poseidon, and ERS-2 along satellite tracks downloaded from the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) web site, were used (AVISO, 2005). Although the ERS-2 altimeter is less accurate than the TOPEX/Poseidon data, the track spatial resolution is much higher (90 km at the equator for ERS-2 vs. 360 km for TOPEX/Poseidon). Moreover, TOPEX/Poseidon has about 10-days repeat of ground track while ERS2 has 35-days repetition. The CorSSH is expressed as:

$$\text{CorSSH} = \text{Satellite Altitude} - \text{Altimeter Range} - \text{Corrections}.$$

where the Satellite Altitude is the distance from the reference ellipsoid of the earth to the satellite, the Altimeter Range is the distance from the sea surface to the satellite, and the Corrections are the correction values such as orbit, ionosphere and ocean tide corrections (AVISO, 2005). Since the CorSSH in the Asian marginal seas contains a relatively large tidal error (Morimoto, 2009), we have to eliminate the tidal error from altimetry data. The altimetry data, removed of tidal signals, was added to the CorSSH to derive the sea surface heights (SSH);

$$\text{SSH} = \text{CorSSH} + \text{Ocean Tide}.$$

The altimeter data used in this present study were from May 1995 to August 2001. Subsequently, tidal signals in the SSH data were removed using harmonic constants derived from TOPEX/Poseidon altimetry data (Yanagi et al. 1997). Again, we could derive the CorSSH data. After removing the tidal signal, the temporal mean of CorSSH at each data point were eliminated leaving the CorSSH anomaly (CorSSHA). Next, the CorSSHA were split into 0.25° grid data using an optimal interpolation method. The covariance functions of signal, $W$, and noise, $\varphi$, used in the optimal interpolation method were as follows:

$$W(|R|, |T|) = W_0^2 \exp\left\{-\left(\frac{|R_x|}{L_x}\right)^2 - \left(\frac{|R_y|}{L_x}\right)^2 - \left(\left\{\frac{|T|}{D}\right\}^2\right)\right\}$$

$$\varphi(\Delta t) = \sigma_0^2 \delta(\Delta t)$$

where $|R_x|$ and $|R_y|$ denote the distance between 2 points, $L_x$, $L_y$ and $D$ are the decorrelation scale in space and time, respectively; $W_o$ and $\sigma_0$ the signal and noise magnitude, respectively, and $\delta(\Delta t)$ is the delta function and is $=1.0$ when $\Delta t=0$ and $\delta(\Delta t)=0$ at any other case. After trial and error, reasonable results were obtained when using $L_x=200$ km in the zonal direction and $L_x=100$ km in the meridonal direction, $D=10$ days, $W_o=$ 4.2 cm and $\sigma_0=7.3$ cm. Once the monthly CorSSHAs were obtained, the temporal fluctuation components of the monthly geostrophic currents were computed using the following equations;

$$f v_a = g\left(\frac{\partial h_a}{\partial x}\right), \quad f u_a = -g\left(\frac{\partial h_a}{\partial y}\right)$$

where $g$ is the earth gravity $\partial h_a$ and is the difference in CorSSHA over $\partial x$ or $\partial y$ distances (0.25°).

Combining the mean geostrophic current, derived from the climatological temperature and salinity data, with the monthly geostrophic current, obtained from the CorSSHA data, we derived the monthly geostrophic current in the GOT for about seven years. Seasonal averaged geostrophic currents were also computed from this seven year period data set. We divided the year into four distinctive seasons. (i) The cool northeast monsoon starts from November and lasts until February and the winds blow mainly from the north to northeast directions. (ii) The first inter-monsoon period lasts from March to April and is the period when the northeast monsoon winds recede and hot south to southeast winds start to blow. (iii) The wet southwest monsoon starts from May and lasts until September, the winds blow mainly from the west to southwest. Finally, (iv) the second inter-monsoon period is in October where the area experiences calm winds, at the end of the southwest monsoon and the starting of the northeast monsoon. The seasonal geostrophic currents were computed according to the above-mentioned periods and the mean seasonal geostrophic currents for 1995–2001 were finally computed.

Vorticity is defined as the spin of an infinitesimal element of fluid about its own axis (Wells, 1986) or the tendency for portions of the fluid to rotate (Pond and Pickard, 1983). It is a vector quantity and directed along the axis of rotation perpendicular to the surface of the fluid element. Positive vorticity is defined as counterclockwise rotation in the northern hemisphere. In the ocean, vertical vorticity can arise from either the current eddy or the velocity shear.

In this study, the relative vorticity was computed from seasonal geostrophic currents. The relative vorticity is defined as $\{(\partial v/\partial x)-(\partial u/\partial y)\}$. Upwelling/downwelling can then be interpreted from the vorticity vector. Positive vorticity can indicate upwelling while negative one can indicate downwelling.

## Results and Discussion

### *General circulation pattern in the Gulf of Thailand*

Fig. 3 displays mean geostrophic current calculated from the mean dynamic topography together with salinity, temperature and sigma-t at the surface. The mean geostrophic current pattern conformed well to the surface salinity, temperature, and sigma-t distribution in terms of the current flow and eddies. There was a strong southwestwards flow along the gulf entrance with a maximum current speed of around 0.3 m/s. The water came from the South China Sea with a high salinity and low temperature. Some portion of the South China Sea water flowed westwards towards the gulf west coast and formed a counter clockwise (CCW) eddy. The CCW eddy was associated with the possible upwelling of water with high salinity and low water temperature. The South China Sea water from the deeper part of the gulf flowed northwards to the east coast, and then turned westwards to form another CCW eddy in the inner gulf. Again high salinity and low temperature in the eddy center indicates the possible upwelling in this region. There are two small clockwise (CW) eddies locating in the south of the inner CCW eddy at the left and right of the northward flow. Water flows into the gulf along the east coast and weakly flows out to South China Sea along the west coast. The magnitude of the mean geostrophic current in the gulf is less than 0.1 m/s.

Figs. 4 and 5 show examples of the monthly variability in CorSSHA derived from the combined TOPEX/Poseidon and ERS-2 altimetry data for the GOT in January and September 1999, respectively. The current magnitude in the gulf was greater than 0.3 m/s, about 2–3 times that of the mean geostrophic current shown in Fig. 3. The GOT experienced a high CorSSHA level during the northeast monsoon season (Fig. 4), which is an indication of an inflow of water mass from the South China Sea during this time of the year. Circulation in the gulf was dominated by CW eddies. On the other hand, low CorSSHA levels occurred during the southwest monsoon season (Fig. 5) because there was an outflow of seawater from the gulf. The circulation in the gulf was dominated by CCW eddies and meandering. Mean sea level fluctuations, computed from tidal records at Lang Suan and Lam Ngob (shown in Fig. 1), confirmed the monthly CorSSHA

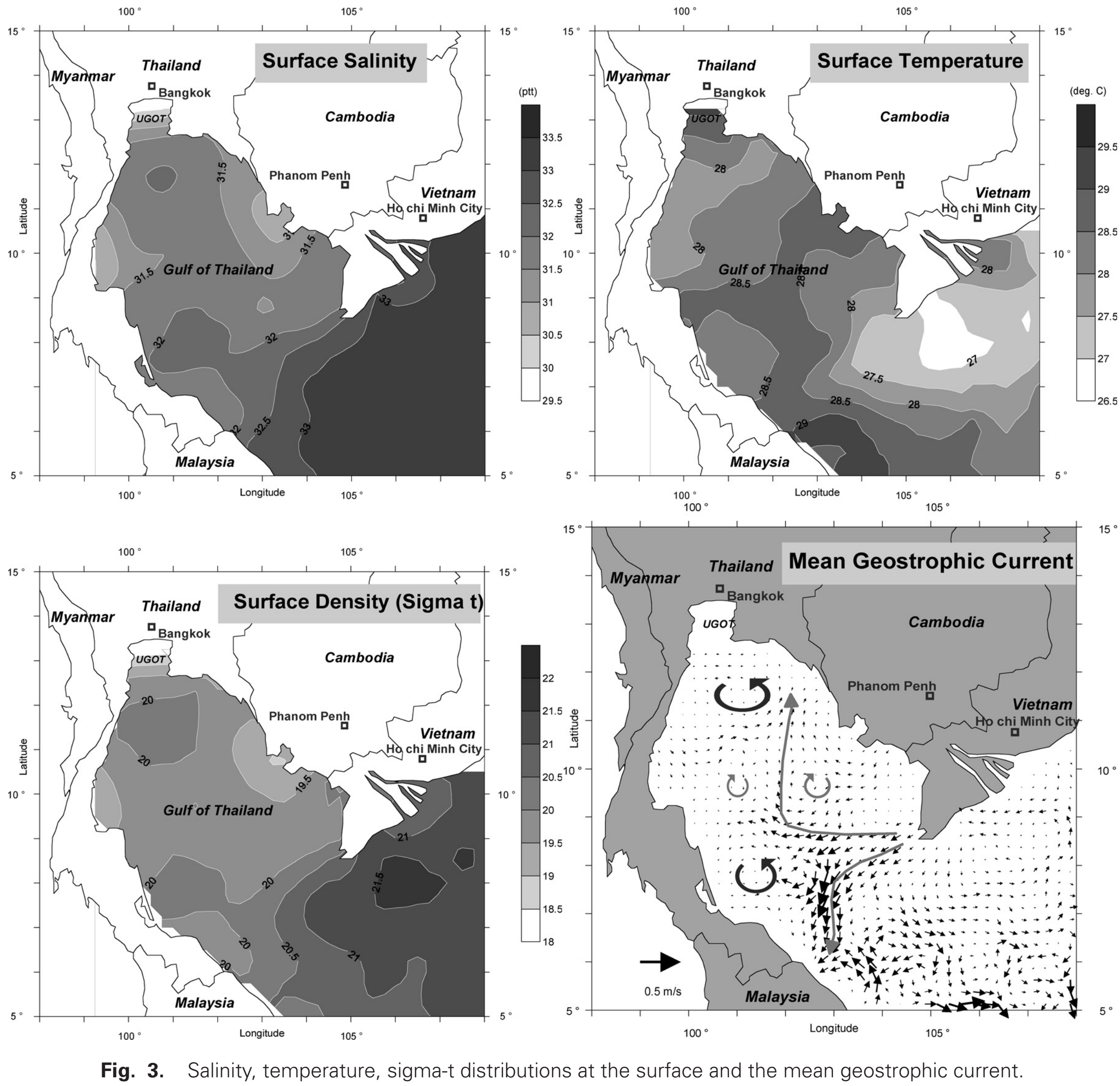



**Fig. 3.** Salinity, temperature, sigma-t distributions at the surface and the mean geostrophic current.

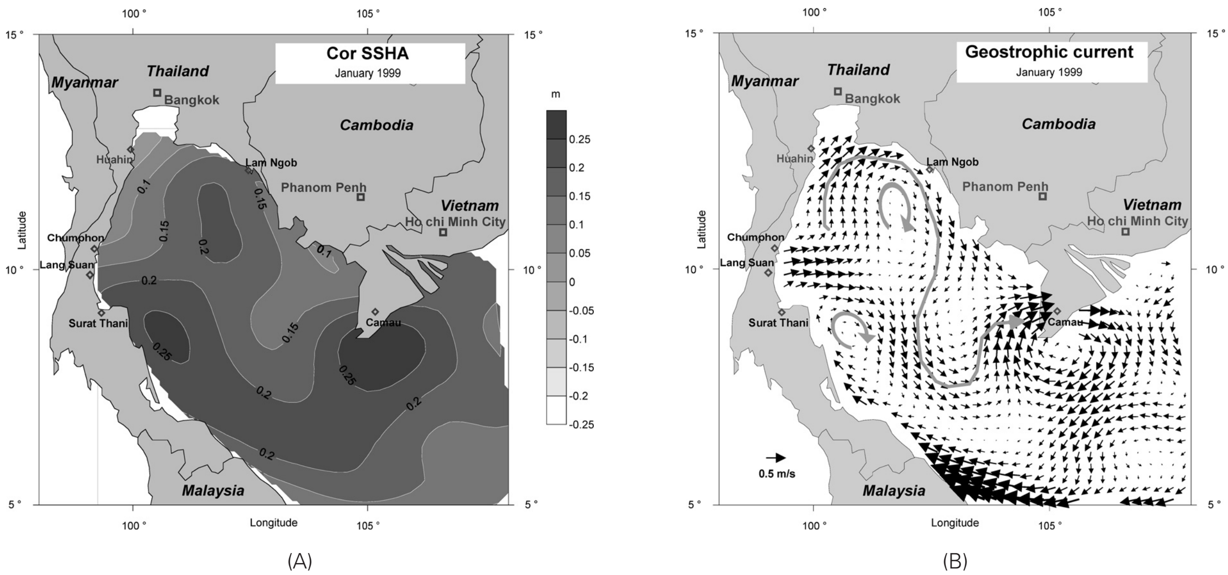



**Fig. 4.** Example of (A) monthly sea surface dynamic height (SSDH, m) and (B) its geostrophic current in January 1999, coinciding with the northeast monsoon season.

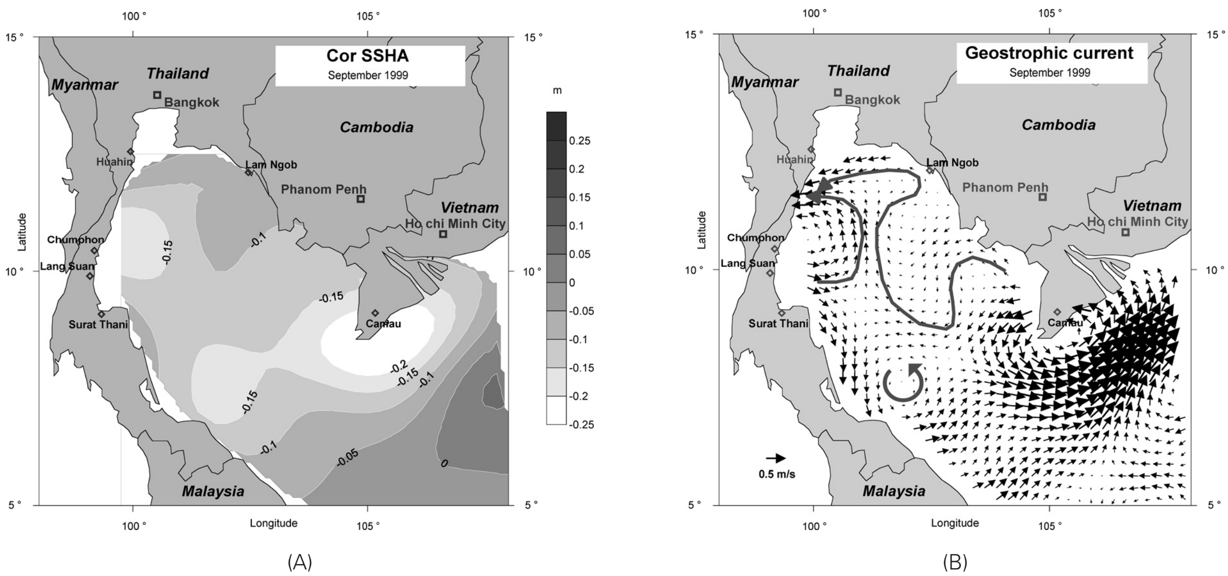



**Fig. 5.** Example of (A) sea surface dynamic height (SSDH, m) and its (B) geostrophic current in September 1999, coinciding with the southwest monsoon season.

fluctuations (Fig. 6).

***Seasonal variation in surface current pattern in the Gulf of Thailand***

Figs. 7–10 display the four seasonally-averaged geostrophic currents, computed from the fluctuated geostrophic current derived from the CorSSHA superimposed on the mean geostrophic current, in the GOT during 1995–2001. The plots of potential vorticity computed from the surface currents are also shown.

*(i) Northeast monsoon period (November to February)*

Fig. 7 shows the average surface current pattern for the northeast monsoon season (November–February). The strong northeast wind brought about a strong southwestwards flow at the gulf entrance. This southwestwards flow was confirmed by the field observation results from the NAGA Expedition (Wyrtki, 1961) and analysis of surface current measurement (Siripong, 1984). When the water encountered the gulf's west coast, it turned right (northwards) and created the basin-wide CW circulation near the coast. Morimoto et al. (2000) also found the basin-wide CW circulation in the gulf during the NE monsoon season. There was also evidence of

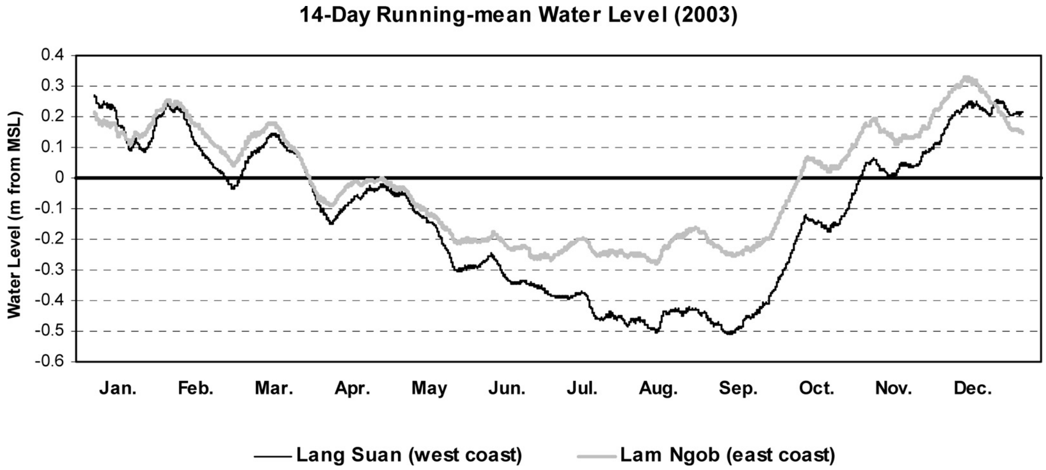
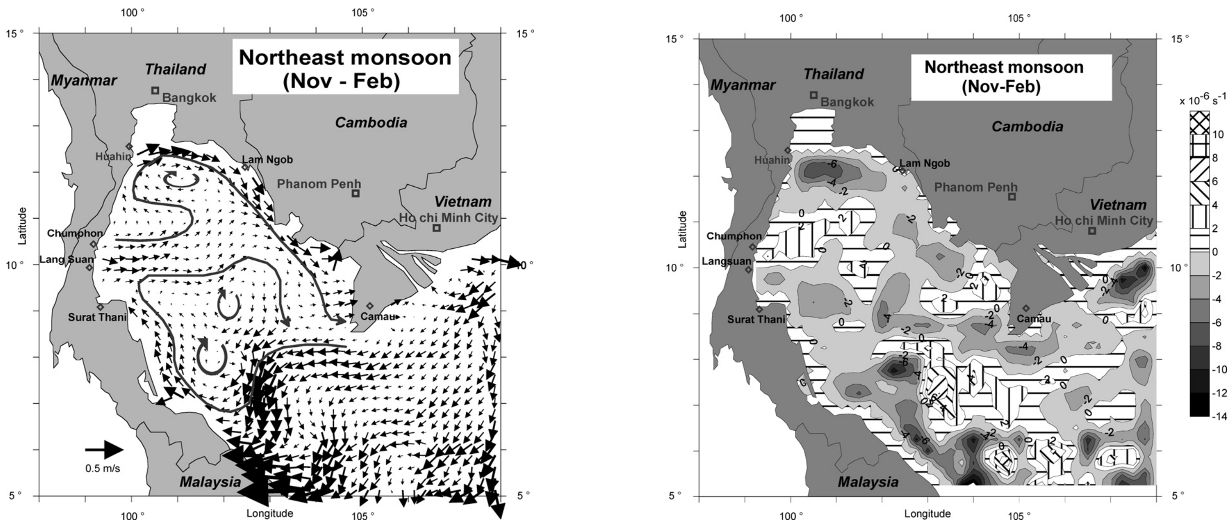



**Fig. 6.** Sea surface variabilities recorded in tidal data from Lungsuan (western coast) and Lam Ngob (eastern coast) tidal stations (see Figure 1 for station location).




(A) (B)

**Fig. 7.** (A) Inter-annual averaged geostrophic current during the northeast monsoon season (top) and (B) vorticity field calculated from the geostrophic current. ↻ represents the CW eddy region while ↺ represents the CCW eddy region.

the northward-bound longshore sediment transport along the southwestern coast during this season (Weesakul, 1992). At 10° latitude, the eastward flow interrupted the northward flow alongshore. The inner gulf was dominated by the eastward flow and a weak CW eddy. A CW eddy and current meandering are located inside the southern loop on the western side of the gulf. The alongshore current (about 0.1 m/s) was stronger than that in the central gulf. The circulation pattern in the gulf obtained from this study was rather complex, somewhat similar to what was found in the theoretical results of Lowwittayakorn's study (Lowwittayakorn, 1998). The weak CW eddy in the inner gulf differed from the CCW eddy suggested by Wyrtki (1961) and the Hydrographic Department (1968). The Hydrographic Department also suggested one big CW eddy in the southern gulf while we found weak eddies and meandering in the same area.

In terms of relative vorticity field in the GOT, negative vorticity and CW eddies exists at the entrance of the inner gulf, at the eastern and western sides of the entrance of the gulf, and along the gulf's eastern coast. There are tendencies for downwelling in these regions. The positive vorticity/upwelling could be found with northward and longshore transport along the lower part of the gulf's western coast, at the central part of the gulf's western coast, at the lower part of the gulf's eastern coast and in the middle of the gulf's entrance. The downwelling areas in the gulf were wider than the upwelling areas during this season. However, the vertical current magnitudes $[(\text{depth}/2)\{(\partial v/\partial x)-(\partial u/\partial x)\}]$ are rather small, being in the order of $10^{-5}$ m/s only (the water mass rose-up/sank-down at about 1 m per day).

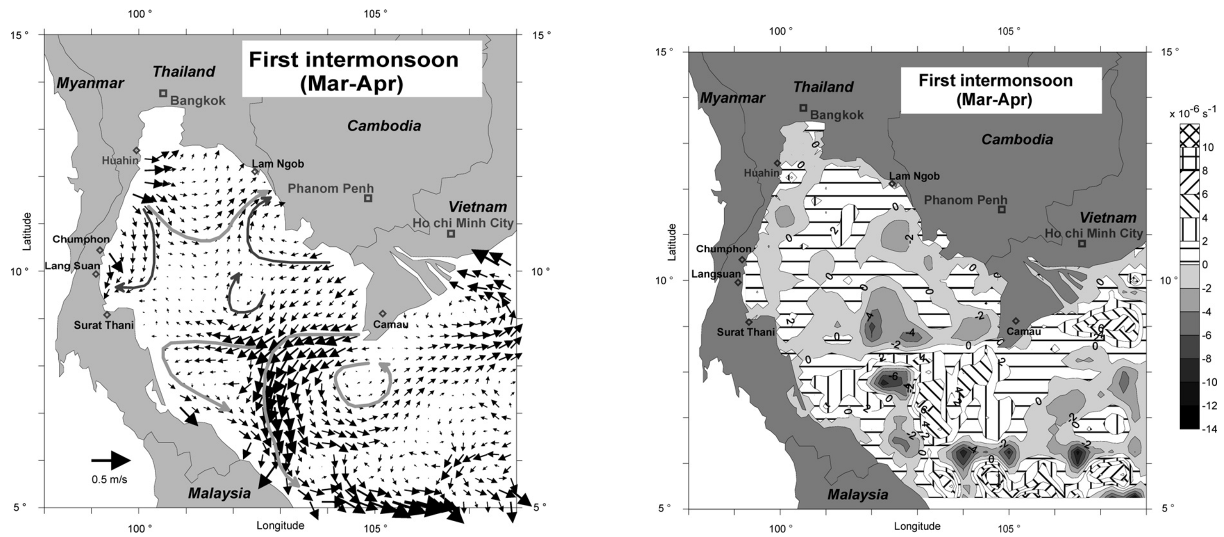
*(ii) Inter-monsoon period (March to April)*

Fig. 8 shows the average surface current pattern during the first inter-monsoon period (March –April), where the prevailing wind changed from a N–NE to a S–SE direction. The area experiences a hot summer due to the incident radiation (sunlight) and warm and humid air from the equator. The surface current field in the gulf resembled that of the mean geostrophic current (Fig. 3), but without the CCW eddy in the inner gulf. The basin-wide circulation in the gulf disappeared during this inter-monsoon period, probably because the wind was rather weak and variable. The westward flow at the gulf entrance was still dominant with the addition of a CCW eddy at the tip of Cape Camau. Strong upwelling (Fig. 8B) occurred due to this CCW eddy. The SE wind shored up the water mass along the western coast of the gulf and this water mass then flowed eastwards to the northeastern coast or flowed southwards to the bay in Surat Thani Province. Because of the pile-up of water along the western coast, weak downwelling was prevalent in this region (see Fig. 8B). The wind and the shear current along the gulf entrance also dragged the water mass from the southeastern coast, and this coastal water flowed either southwestwards or northwards. The current shears created both upwellings and downwellings along the eastern coast of the gulf. The CCW eddy and the current shear in the lower central part of the gulf also created a strong downwelling there.

When comparing the studied result to the field observations carried out in April 1960 during the NAGA expedition (Wyrtki, 1961), neither a CCW eddy in the inner gulf nor a southward flow from the inner gulf to the southern opening were detected in this study. The reason was that the sampling stations were too sparse to resolve the sub-basin scale eddy in the gulf. In addition, the basin-wide CCW circulation suggested by the Hydrographic Department (1961) was not detected. One explanation for the discrepancy is that the prevailing wind varies from year to year, and this affected the circulation pattern in the gulf. Our study (not shown) has indicated that there were some inter-annual variabilities among the seasonal geostrophic current.

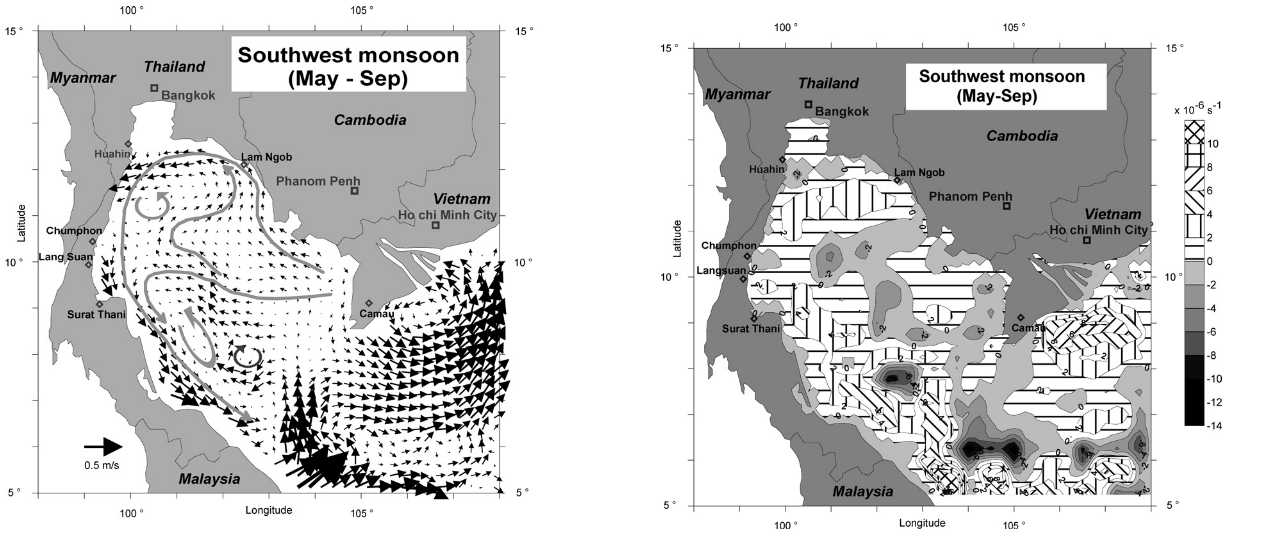
*(iii) Southwest monsoon period (May to September)*

Fig. 9 displays the average surface currents during the southwest monsoon (May - September), which is the rainy season, with strong W to SW winds from the Indian Ocean. The circulation pattern was almost the opposite to that seen during the northeast monsoon season (see (i) above). The SW wind caused a strong northward flow from the western coast outside the gulf. Part of the current turned eastwards at the mouth of the gulf, bringing water along the southeastern part out of the bay. The continued northward flow at the gulf center initiated the basin-wide CCW circulation, similar to what has been suggested by several authors previously (Wyrtki, 1961; Morimoto et al., 2000). However, the circulation pattern was more complex than that previously thought. There were two CCW eddies on the western side and inside the basin-wide CCW circulation. The CCW eddies enhanced upwelling from the northern part of the inner gulf to the western side of the gulf (see Fig. 9B). A small-size CW eddy was found coupling with the lower CCW eddy. This CW eddy (and hence downwelling) was found throughout the year but its location moved from season to season. The current shears induced downwelling in the lower central part and in the middle and southeastern coast of the gulf. The current shear also induced upwelling in the middle of the eastern coast. Over all, the upwelling area was wider than the downwelling area, but the vertical current magnitudes were small



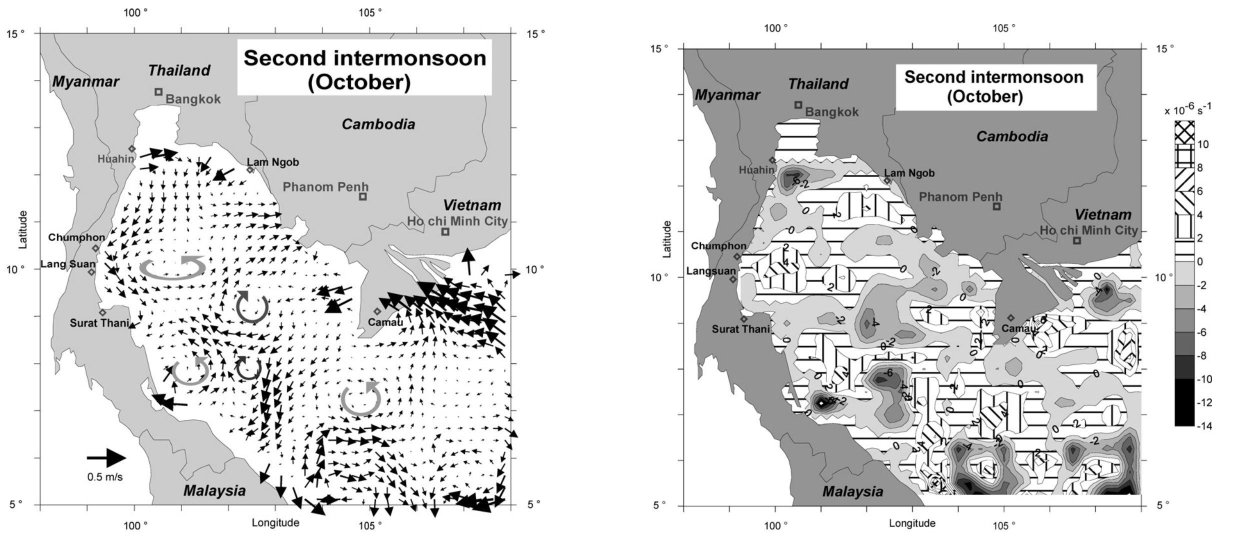

(A) (B)

**Fig. 8.** (A) Inter-annual averaged geostrophic current during the first inter-monsoon period (top) and (B) vorticity field calculated from the geostrophic current. ↻ represents the CW eddy region while ↺ represents the CCW eddy region.




(A) (B)

**Fig. 9.** (A) Inter-annual averaged geostrophic current during the southwest monsoon season and (B) vorticity field calculated from the geostrophic current. ↻ represents the CW eddy region while ↺ represents the CCW eddy region.




(A) (B)

**Fig. 10.** (A) Inter-annual averaged geostrophic current during the second inter-monsoon season and (B) vorticity field calculated from the geostrophic current. ↻ represents the CW eddy region while ↺ represents the CCW eddy region.

($\sim 10^{-5}$ m/s). The SW wind induced surface Ekman current that flowed southeastwards and brought surface water out of the gulf. Thus, the Ekman current might enhance the upwelling during this season.

Wyrtki (1961), during field observations in September 1960, suggested the presence of the basin-wide CCW circulation with upwelling near the west coast and small downwelling (CW eddy) in the gulf center. The result of this study confirmed his suggestion. But the circulation near the mouth of the gulf was somewhat different. The circulation pattern proposed by the Hydrographic Department (unpublished) also differed from what has been found in this study.

*(iv) Inter-monsoon period (October)*

Fig. 10 shows the average surface current pattern during the second inter-monsoon period (October). The wind was calm and varied from SW to NE depending on the strength of each monsoon during each year. The prior northward and eastward flows at the mouth of the gulf changed into westward and southward flows, and the basin-wide CCW circulation in the gulf disappeared. The CW eddy on the western side near the mouth of the gulf was, however, still present. The circulation in the gulf was full of meandering and eddies. The water mass from the inner gulf flowed southwards and diverted into the southwestward flow and the eastward flow when it met a CCW eddy in the central gulf. The southwestward current flowed along the gulf west coast and turned around the CCW eddy in the central gulf and converged with the eastward current again. The CCW eddy associated with the upwelling might be residual from the SW monsoon season (Wyrtki, 1961). Another upwelling area was along the southwestern coast where a CCW eddy existed (Fig. 10B). There appeared to be a CW meandering with a CW eddy in the center at the southeastern side of the gulf, and this is located where downwelling would occur. As seen earlier in other seasons, current shears at the middle and at the eastern side of the gulf entrance created a strong upwelling in that location. The upwelling and downwelling areas observed during this season conformed to those from the field survey by the NAGA Expedition during October, 1959 (Wyrki, 1961).

**Relationship between the circulation pattern and spawning behaviors of the short-bodies mackerel in GOT**

One application of characterizing the GOT circulation is to help the understanding of the migration and spawning behaviors of the short mackerel *Rastrelliger brachysoma* (Bleeker, 1851) and indian mackerel *Rastrelliger Kanagurta* (Cuvier, 1817), which are pelagic fish that live in schools. These fish used to be a cheap and widely available staple food and protein source for Thai people but heavy over-fishing in the gulf has caused the decline in fish population and age structure, with lower fish stock levels and fewer of the remaining fish surviving long enough to reach maturity (about 178 mm). Declined mackerel catch in the early 1960's decade has led to the mackerel investigation project by the Thai Fishery Department (Menasaveta, 1965). Three separate studies have suggested that there might be two sub-populations of the mackerel, one sub-population living in the eastern side of the gulf and migrating between the Thai coast and the Cambodian coast, whilst the other subpopulation lives in the western side and migrates into the UGOT (Chomjurai et al., 1965; Vanichkul and Hongskul, 1965; Maila-iad et al., 2006). Every year the fish come to spawn in the middle of the western coast, roughly bounded by Prachuab Kirikhan to Surat Thani Provinces (see Fig. 1) and the 100°15′E longitudinal line. However, a recent study of the genetic diversity of *R. brachysoma* (Srinulgray, 2008) indicated that there are two sub-populations in the gulf, one sub-population living in the upper part of the gulf (both western and eastern sides and in the UGOT) and another one living in the lower part of the gulf (below Surat Thani Province).

Fish congregation occurs in February–March and spawning and rearing occur in April–May. Chamchang (1991) carried out sampling of larval fishes in the water of the Gulf of Thailand between Prachuab Kirikhan to Surat Thani Provinces, using plankton nets, from Jan.–Dec. 1985 and found that the *Rastrelliger spp.* spawned in this area during Jan.–Mar. and Jul.–Aug. By studying the maturity of the fish, three separate studies concluded that the *Rastrelliger spp.* can spawn all year round with the peak spawning at the above mentioned periods (Maila-iad et al., 2006; Sritakon et al., 2006). After spawning, the larval fish migrated to the nearshore zone where the food was more abundant and there were less predators. After August, the young fish start to migrate into the UGOT where they remain to reach the mature stage. In December–January, the mature fish migrate back to the western coast of the gulf and start a new spawning season. For decades, the Fishery Department has declared the spawning ground off-limits to the fishermen during Feb. 15–May 15 (http://www.fisheries.go.th/DOF_THAI/Information/CloseBay/index/htm). The spawning ground is bounded by Lat. 11°49′40″N, Lat. 9°15′00″N, Long. 100°15′00″E and the western coast. The so called "Close Bay Measure" is vital to the maintaining the stock of the *Rastrelliger* spp. in the GOT.

From our study we found that the fish life cycle matches up with the circulation and upwelling patterns quite nicely. Peak fish congregation and spawning during January–April occur before the onset of upwelling along the western coast during the SW monsoon periods (Figs. 7–9). During the SW monsoon period, the upwelling occurred both in the coastal and offshore area of the gulf and larvae and grown-up fish spend their time in this region. In October, the upwelling in the gulf is reduced and the fish migrate to the upper gulf where nutrients from river discharge and phytoplankton are plentiful. The fish then spend time growing up in the upper gulf region during the NE monsoon when downwelling occurred in most areas of the gulf (Fig. 7). Thereafter the fish swam back to spawn again in the western gulf by the end of the NE monsoon and the first monsoon period. However, to be sure of our suggested correlation, field studies must be carried out to confirm the circulation and upwelling patterns in the area as well as fish migration patterns.

**Summary**

We computed total geostrophic circulation through the use of world ocean climatological database and TOPEX/Poseidon & ERS-2 altimetry data. The mean geostrophic current from the climatological temperature and salinity data showed a water mass from the South China Sea flows strongly southwestwards and westwards along the gulf entrance. There are two upwelling areas associated with the CCW eddies. One eddy is located in the inner gulf and another one is located at the western side of the gulf entrance. Seawater and river discharge on the eastern side of the gulf flow northwards while a southward flow occurs over on the western side.

The CorSSHA data showed water set-up and set-down in the GOT were in accordance with the prevailing NE and SW monsoon winds. The combined geostrophic current patterns showed a basin-wide circulation with eddies and meanderings within it. This basin-wide CCW circulation existed during the SW monsoon season and upwelling in the gulf was enhanced during this season. The basin-wide CW circulation exists during the NE monsoon season and downwelling in the gulf is prevalent during this season. The circulation patterns and eddies are somewhat in agreement with the previous studies of other authors, but not in all cases. It is unclear if these discrepancies represent recent actual changes in current patterns within the GOT, or simply differences in the methodologies and parameters used between these studies.

Finally, we tried to link the gulf circulation with the life cycle of the short mackerel, *Rastrelliger spp.,* in the gulf. It seems that their congregation and spawning coincided with the upwelling along the western coast. Also the migration routes concur with the current circulation patterns in the GOT. But further investigation is needed in order to confirm our findings.

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