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## การไหลเวียนของกระแสน้ำในอ่าวไทยตอนบนจากการศึกษาโดยใช้แบบจำลองไฮโดรไดนามิก 3 มิติ

### Circulation in the Upper Gulf of Thailand

#### Investigated Using a Three-Dimensional Hydrodynamic Model

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#### บทคัดย่อ

แบบจำลองไฮโดรไดนามิก Princeton Ocean Model (POM) ได้ถูกนำมาใช้ศึกษาการไหลเวียนเชิง 3 มิติของกระแสน้ำในอ่าวไทยตอนบน โดยพิจารณา ลม น้ำขึ้น-น้ำลง และน้ำท่า เป็นแรงขับเคลื่อนที่สำคัญ ผลที่ได้แสดงให้เห็นถึงการเปลี่ยนแปลงตามฤดูกาลของรูปแบบการไหลเวียนของกระแสน้ำที่สอดคล้องกับทิศทางของลมมรสุม กระแสน้ำที่ผิวทะเลเคลื่อนที่ไปตามทิศทางของลม ในขณะที่กระแสน้ำในที่ลึกลงไปมีทิศทางตรงข้าม เกิดจากการไหลแทนที่น้ำที่ผิวทะเล ไตเวอร์เจ้น (divergence) และคอนเวอร์เจ้น (convergence) ที่ผิวทะเลสอดคล้องกับการเกิดปรากฏการณ์น้ำผุด (upwelling) และน้ำมุด (downwelling) ตามลำดับ จากการคำนวณค่ากระแสน้ำเฉลี่ยตลอดความลึกพบว่า เกิดการไหลเวียนแบบตามเข็มนาฬิกาในช่วงลมมรสุมตะวันตกเฉียงใต้ และแบบทวนเข็มนาฬิกาในช่วงลมมรสุมตะวันออกเฉียงเหนือ รูปแบบการไหลเวียนกระแสน้ำที่ผิวทะเลจากแบบจำลองมีความสอดคล้องกับค่าที่ได้มาจากการตรวจวัด อย่างไรก็ตาม พบความไม่สอดคล้องของผลการเปรียบเทียบในเดือนกรกฎาคม ซึ่งอาจเกิดจากลักษณะของลมที่แตกต่างกันในแต่ละปี อิทธิพลของน้ำจากตอนกลางของอ่าวไทย อิทธิพลของน้ำท่าหรือจากลักษณะธรณีลักษณะฐานของพื้นทะเล จึงควรที่จะต้องทำการศึกษากันต่อไปในอนาคต ถึงปัจจัยและกลไกของการเกิดปรากฏการณ์ดังกล่าว

**คำสำคัญ :** แบบจำลองไฮโดรไดนามิก กระแสน้ำ อ่าวไทยตอนบน

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## Abstract

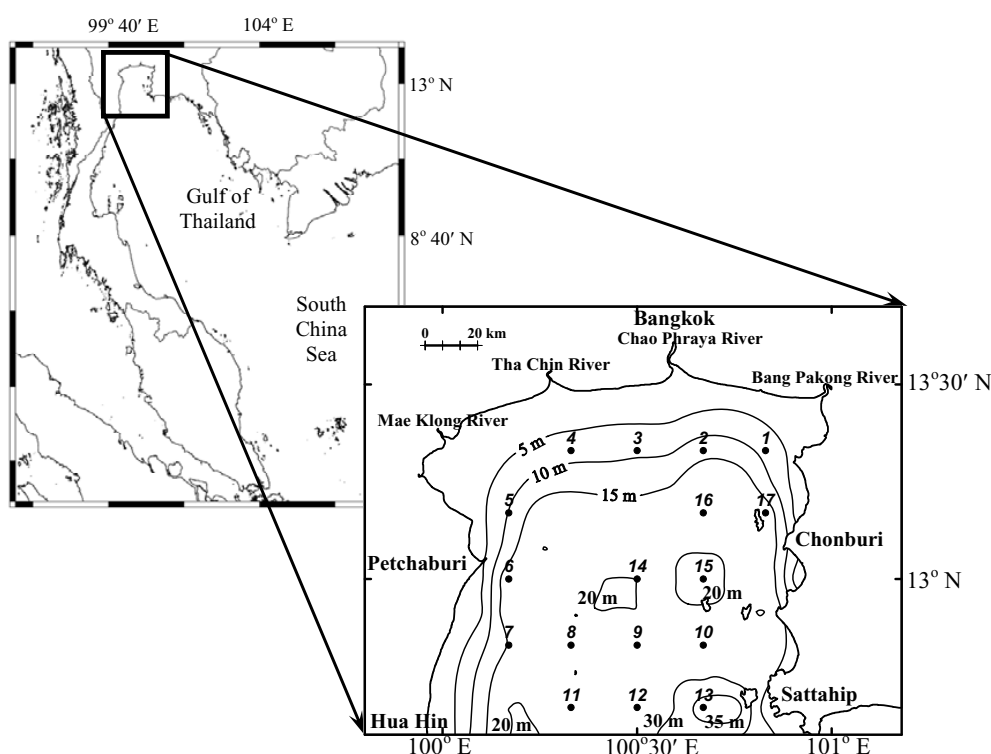
The Princeton Ocean Model (POM) was applied to investigate three-dimensional circulation in the upper Gulf of Thailand (UGoT). Wind, tide and river discharge were considered as major forces for the numerical experiments. The simulated results revealed seasonal variation in circulation patterns associated with monsoonal winds. Surface currents always moved downwind, generating reverse circulation caused by the replenishment of water in deeper layers. Surface divergence and convergence were observed to correspond to the development of upwelling and downwelling, respectively. Clockwise and counter-clockwise circulation during the southwest and the northeast monsoon influences, consecutively, were prominent in the resulting depth-averaged circulation. The simulated surface currents were validated and found to agree with the observed data. Reverse circulation patterns, however, appeared in July. This could be possibly generated from interannual variations in wind patterns, interaction of water from the central GoT, influence from river discharge, or bottom topography. Further investigation is required to clarify the factors and mechanisms relevant to this phenomenon.

**Keywords** : seasonal circulation, POM, The upper Gulf of Thailand

## 1. Introduction

The upper Gulf of Thailand (UGoT) locates in the south of Bangkok (Figure 1). It is the first place to receive contaminants transported to the coast by four major rivers, including the Chao Phraya, the largest river in Thailand, before transported farther to the central GoT. Several reports, including Chongprasith and Srinetr (1998), Cheevaporn and Menasveta (2003) and Wattayakorn (2006) have addressed concerns regarding water pollution problems in the area. Understanding of the dynamics of

contaminants is quite limited due to inadequate knowledge of complex coastal and other environmental processes. The interaction of current, wind, tide and river discharge, and their strong seasonal variability following monsoonal influences also add complexity to environmental conditions. These highlight the need of synoptic oceanographic research to increase our understanding of the dynamics of material transport in this coastal sea.



**Figure 1** The upper Gulf of Thailand, contour lines representing water depth in meters and dots for observational stations.

Buranapratheprat et al. (2002, 2006) applied a two-dimensional model to investigate seasonal circulation in UGoT. Clockwise and counter-clockwise circulation covering the entire area was found to develop during the southwest (wet season) and the northeast monsoons (dry season), respectively. Water column stratification attributed to the influx of fluvial discharge dominates, especially during the wet season (Bunpapong and Piyakanchana, 1987).

They were unable, however, to integrate this influence into the two-dimensional simulation. Such limitations, together with both horizontal and vertical water movement and subsequent material transport, point to the importance of understanding and characterizing water circulation profiles. This is the objective of the present study which is to investigate circulation in UGoT by using a three-dimensional diagnostic model.

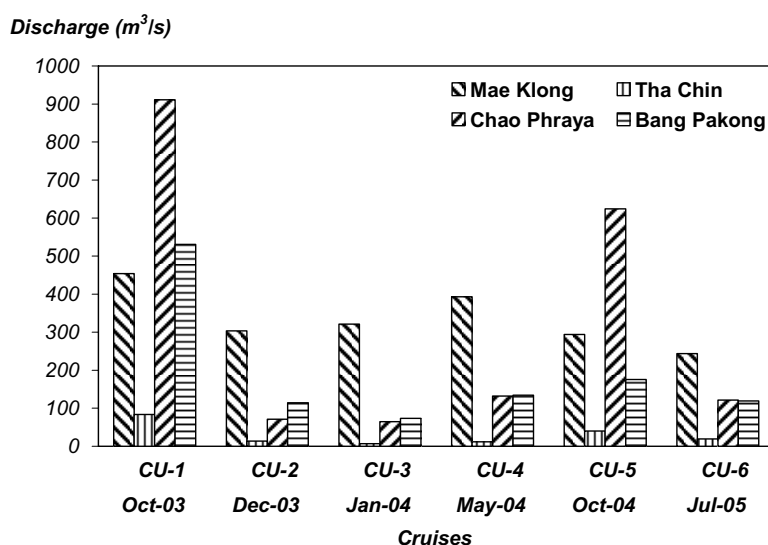
## 2. Data sources

Input data for the numerical experiments including bathymetry, salinity, temperature, river discharge, wind, and tide were derived from several sources. The 5-Minute Gridded Global Relief Data (ETOPO5), a global bathymetry dataset, were provided by the World Data Center for Marine Geology & Geophysics, available through <http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO5/>. In-situ temperature and salinity profiles, probed using a Conductivity-Temperature-Density sensor (CTD) at 17 stations throughout the UGoT area from 6 observational cruises (Table 1), were obtained from the Department of Marine Science, Faculty of Science, Chulalongkorn University, Thailand (Matsumura et al., 2006). The cruises

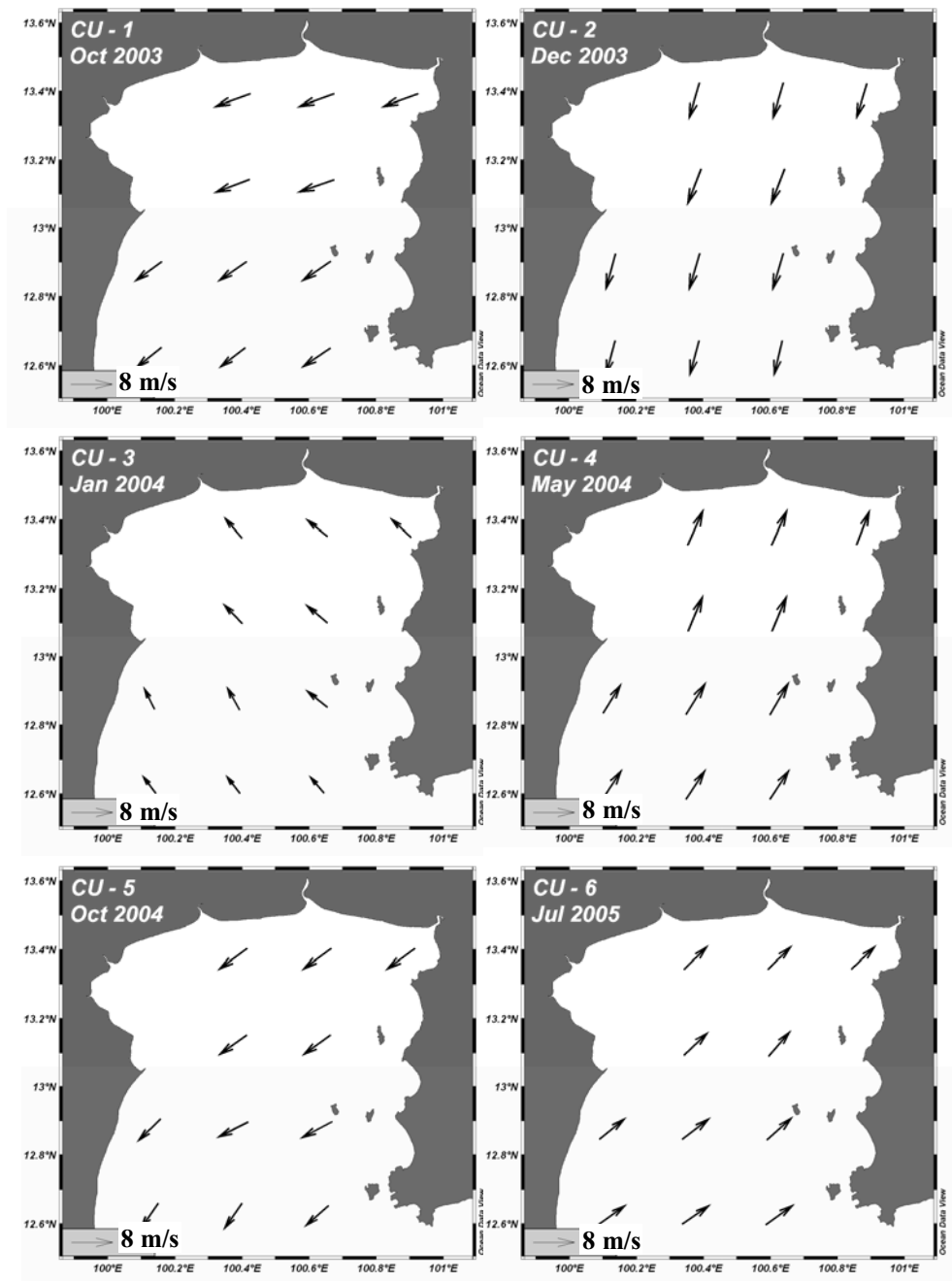
covered both the northeast and the southwest monsoonal seasons. The discharge of four main rivers (Figure 2), used as a boundary condition at the river mouths, were collected by the Royal Irrigation Department (RID) of Thailand. Monthly mean wind data from QuickScat in the same months of field observations (Figure 3) were downloaded from <http://www.ssmi.com>. Water elevations in the east (Sattahip) and the west (Hua Hin) of the sea boundary were computed by using a harmonic analysis technique.  $K_1$ ,  $O_1$ ,  $M_2$  and  $S_2$  are major tidal harmonic constituents where their amplitudes and phases at Sattahip and Hua Hin (Table 2) were reported in Sojisuporn and Putikiatikajorn (1998). Water level data between both ends were then derived using a linear interpolation.

**Table 1** A list of cruises for oceanographic observations.

Cruise name	Date
CU-1	9 - 11 October 2003
CU-2	4 - 6 December 2003
CU-3	13 - 15 January 2004
CU-4	12 - 15 May 2004
CU-5	7 - 10 October 2004
CU-6	26 - 28 July 2005



**Figure 2** Monthly mean discharge in the same months of observational cruises of four major rivers emptying into the head of the upper Gulf of Thailand (source: The Royal Irrigation Department of Thailand).



**Figure 3** Monthly mean wind field of QuickScat in the same months of observational cruises (source: <http://www.ssmi.com>).

**Table 2** Tidal harmonic constituents used to calculate water elevation at the sea boundary.

Harmonic Constituents	Hua Hin		Sattahip	
	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
K <sub>1</sub>	61.2	155.1	58.7	162.0
O <sub>1</sub>	39.0	119.2	29.3	112.0
M <sub>2</sub>	29.7	139.9	26.1	121.0
S <sub>2</sub>	15.3	212.8	12.3	192.0

### 3. Numerical experiments

The Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) was applied to simulate three-dimensional circulation of UGoT. This model is suitable for application in a coastal sea because the vertical grid spacing, in terms of sigma ( $\sigma$ ) layer, was well designed to follow variations in shallow bottom topography. Details of POM, including a mathematical description are continued in Blumberg and Mellor (1987), and Mellor (1998).

The study area was divided horizontally into 124 102 grids using spherical coordinates with a grid spacing of 0.5 minutes. The vertical domain was set to 10  $\sigma$ -levels without logarithmic portions. Measured salinity and temperature were interpolated three-dimensionally using a Gaussian method to fit the data to the grid-spacing of the computational domain. Monthly averaged winds were also interpolated to fit all horizontal grids, and used as a surface driving force. Tidal currents, as water elevations, were set to drive the water system through sea boundary.

#### 3.1 Lateral boundary conditions

At the river boundaries, discharge was transformed to water level and added to water elevation of computational grids at the river mouths. This method is based on the concept of continuity of incompressible fluid dynamics described in Kourafalou et al. (1996). Elevated water owing to discharges flows to surrounding grids following surface slope and driving forces such as wind and tide. This technique not only provides for flexible river flows, but also helps to increase model stability by reducing overflow near the river mouths.

The sea boundary is forced by tidal action via water elevations which are transformed to velocities in the model through the continuity equation. During model operation, water elevations along the sea boundary are updated in every external time step (two-dimensional mode) under radiation condition (Mellor, 1998), illustrated by the following equation.

$$H\bar{U}_B = H\bar{U}_{B-1} \pm C_e \eta, \quad (1)$$

$$C_e = \sqrt{gH},$$

where  $\bar{U}$  is the vertically averaged velocity ( $\text{m s}^{-1}$ ), normal to the boundary; subscripts  $B$  and  $B-1$  are referred as values at the boundary and at a consecutive grid inside computational domain respectively;  $H$  is water depth (m),  $\eta$  is water elevation (m);  $g$  is the gravitational acceleration ( $\text{m s}^{-2}$ ); and  $C_e$  is long-wave phase speed ( $\text{m s}^{-1}$ ).

Components of velocities perpendicular to land boundaries are set to be zero while radiation condition is also assigned at the sea boundary of the internal mode (three-dimensional mode) as shown in the following equation.

$$U_B^n = GAI \cdot U_{B-1}^{n-1} + (1-GAI) \cdot U_B^{n-1}, \quad (2)$$

$$GAI = \sqrt{\frac{H}{H_{\max}}},$$

where  $U$  is velocity normal to the boundary ( $\text{m s}^{-1}$ );  $n$  and  $n-1$  are referred as present and previous time steps, respectively; and  $GAI$  is a weighing factor which is dependent on water depth and the maximum depth ( $H_{\max}$ ) (m). Finally, open boundaries for salinity, temperature, and

turbulence are set by a condition called “upstream advection” as defined in Eq. 3.

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = 0, \quad (3)$$

where  $T$  is referred to those parameters; and  $t$  (s) and  $x$  (m) are time and length, respectively.

### 3.2 Model operation

The model was operated using the robust diagnostic technique by adding the damping terms,  $\gamma (T^* - T)$  and  $\gamma (S^* - S)$ , to the temperature and salinity equations, respectively. Here,  $\gamma$  is referred to as the nudging constant ( $= T_i / (86,400 \text{ s} \times 5)$ );  $T_i$  is internal time step (300 s).  $T$  and  $S$  are calculated water temperature and salinity, respectively; the parameters with a superscript (\*) represent the observed values. A small  $\gamma$  makes the modeling approach prognostic, while a large  $\gamma$  will restrict conditions of calculated  $T$  and  $S$  to be close to the observed values, which favor diagnostic operation (Yanagi, 1999).

The model was set to have no exchanged heat and salt fluxes from the atmosphere, or the sea bottom, because they were considered to be insignificant, compared to wind, discharge, and tide. Seawater state was set initially at rest ( $t = 0$ ). Time steps of 10 s and 300 s were used for the external and the internal modes, respectively. The model was driven by all forces from start until a quasi-steady state was achieved at days 10. Computed circulation for 30 days after days 20 were averaged to present as residual circulation. Three- and two-dimensional circulation results in the form of vector plots and contour maps were processed by using the Ocean Data View (ODV) software (Schlitzer, 2007).

## 4. Circulation results

### 4.1 Three-dimensional circulation

Monthly mean horizontal circulation at the sea surface, and 10 m depth of corresponding months to the observational cruises (Table 1) are illustrated in Figures 4a and 4b. The results of mean vertical circulation at a

5 m depth are presented in Figure 5. Wind patterns in Figure 3 are also used to explain the seasonal variations in dominant circulation patterns.

Current velocities in October 2003 and October 2004 were quite strong, flowing to the west following wind directions from the northeast. Most surface water came into UGoT from the east and moved out in the west. Divergence of flow at the sea surface appeared in northwestern area close to the Mae Klong River (located in the west of the northern coast in Figure 1) in both years, but those observed in October 2003 appeared to be stronger. A counter-clockwise gyre at 10 m depth in the north was clearly observed during both periods while the second one in the south near open boundary emerged just in October 2004.

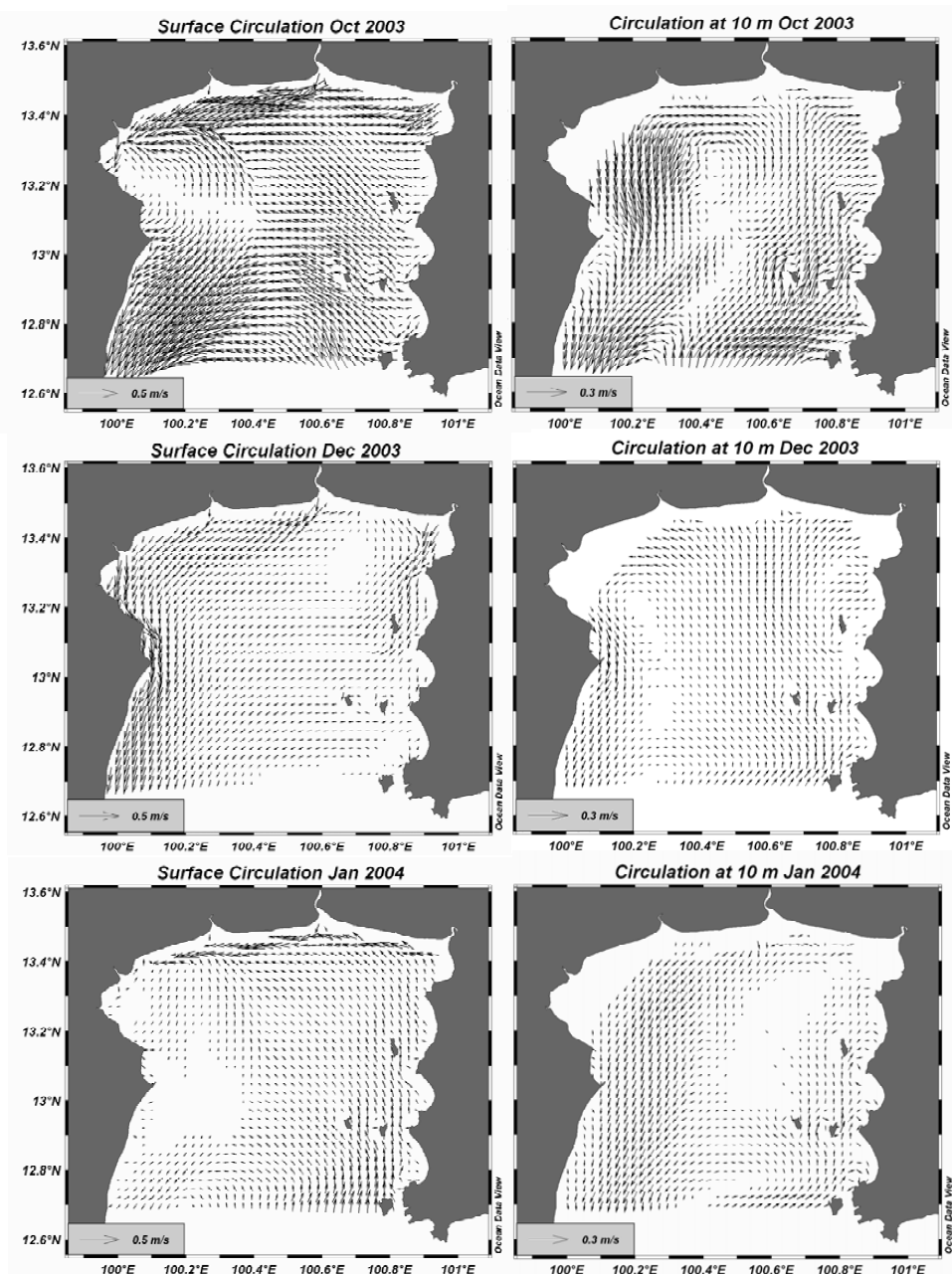
Surface currents in December 2003 moved out of UGoT through the western boundary following winds from the southwest. Moderate-speed currents ( $0.2 - 0.3 \text{ m s}^{-1}$ ) flowed along the western coast, from the Chao Phraya River mouth towards the sea boundary. Most currents at 10 m depth ran into UGoT to compensate outflow surface currents. They also tended to flow into the region along the east coast and out along the west coast.

The southeast wind drove surface water northwestward in January 2004. Some residual weak currents remained, flowing out through the western boundary. Weak current divergence occurred near the central of western coast. The deeper current moved counter-clockwise, similar to those in October and December 2003. In both May 2004 and July 2005 wind directions, which were mainly from the southwest, were almost opposite to those experienced in December 2003. Surface water responded by moving into UGoT from southwest toward northeast. Water along the western coast moved northward instead of southward as in the months when northeast winds prevailed. Currents at 10 m depth ran into and out of UGoT through the western and eastern boundaries, respectively. A clockwise gyre developed in the northwestern area where a counter-clockwise gyre developed in December 2003.

Vertical circulation at 5 m depth (Figure 5) used to study upwelling and downwelling, were found to correspond to divergence and convergence conditions of surface circulation. Coastal divergence happens when currents near the coastline flow seaward, bringing water offshore, and upwelling by replenishment of deeper water results. Conversely, if surface currents run shoreward, which is a case of coastal convergence, downwelling occurs. Upwelling and downwelling along eastern and western coastlines, respectively, were generated when easterly

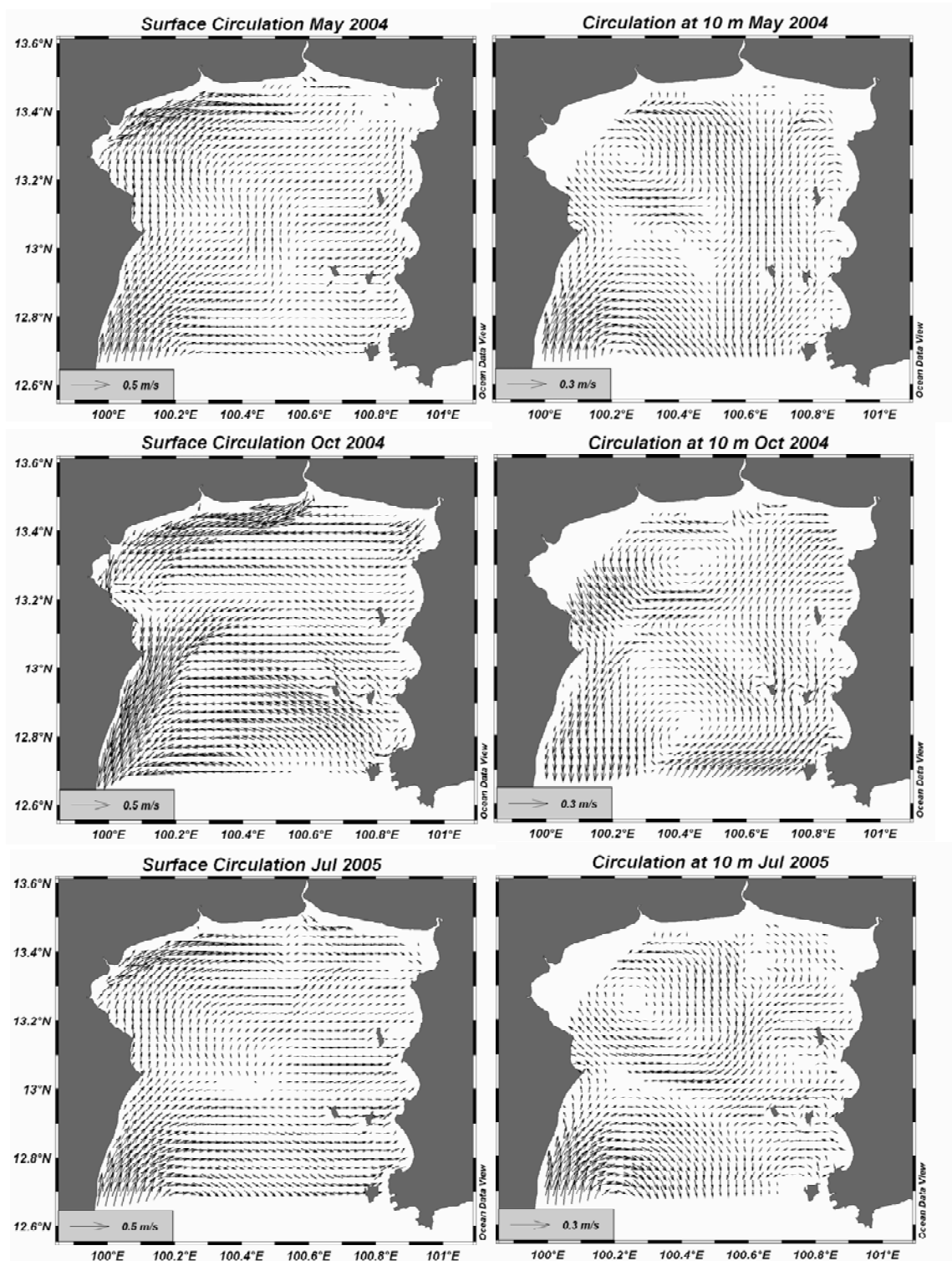
winds prevailed. The situation reversed when wind directions changed to the west.

In offshore regions, divergence and convergence at the sea surface were generated when currents moved apart and moved toward each other, respectively. Upwelling in the middle of the western coast in October 2003 and 2004 was explained by the strong divergence of surface current over the area (Figures 4a and 4b). Convergence in the north of this area, which was responsible for strong downwelling, is also explained by this mechanism.

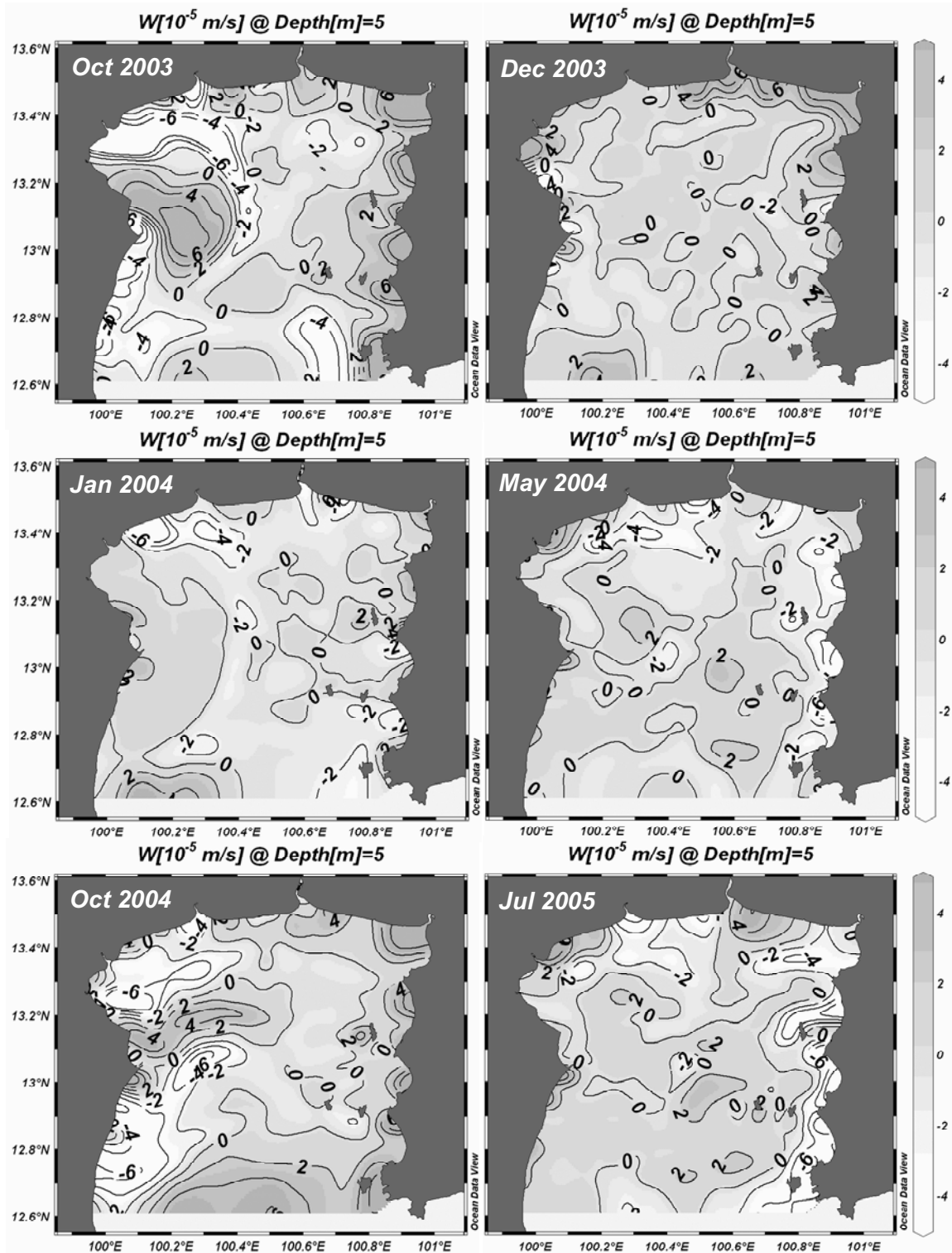


**Figure 4a** Monthly mean horizontal circulation at the sea surface and 10 m depth, simulated using POM, in October 2003, December 2003 and January 2004.





**Figure 4b** The same as Figure 4a but for May 2004, October 2004 and July 2005.

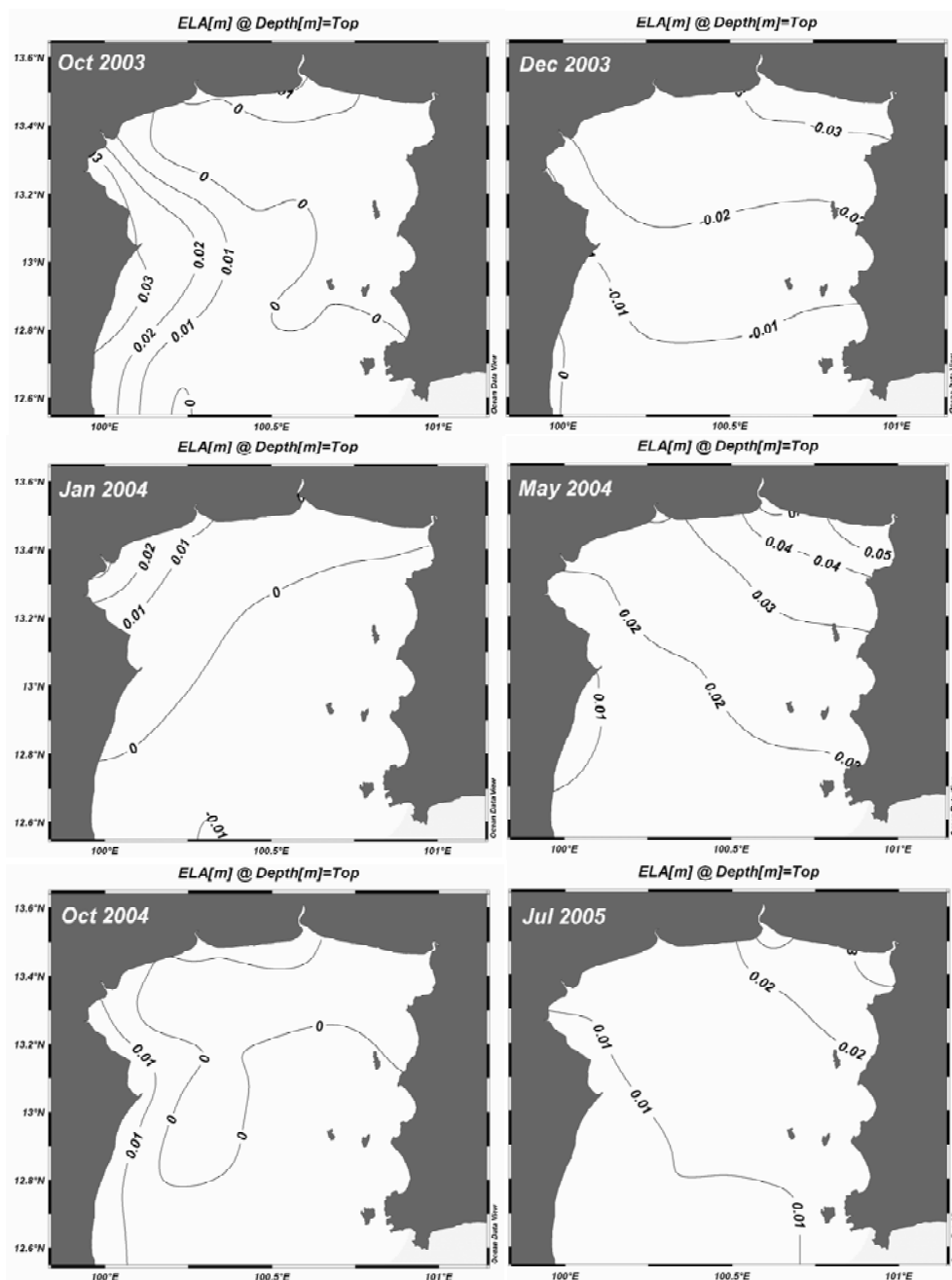


**Figure 5** Monthly mean vertical circulation, simulated using POM, in the same months of observational cruises.

#### 4.2 Two-dimensional results

Two-dimensional circulation results, averaged sea surface elevations, and vertically integrated currents are presented and discussed below. Monthly mean sea level (Figure 6) indicates water pile-up in downwind areas. Sea levels rose when winds flowed landward in all experimental

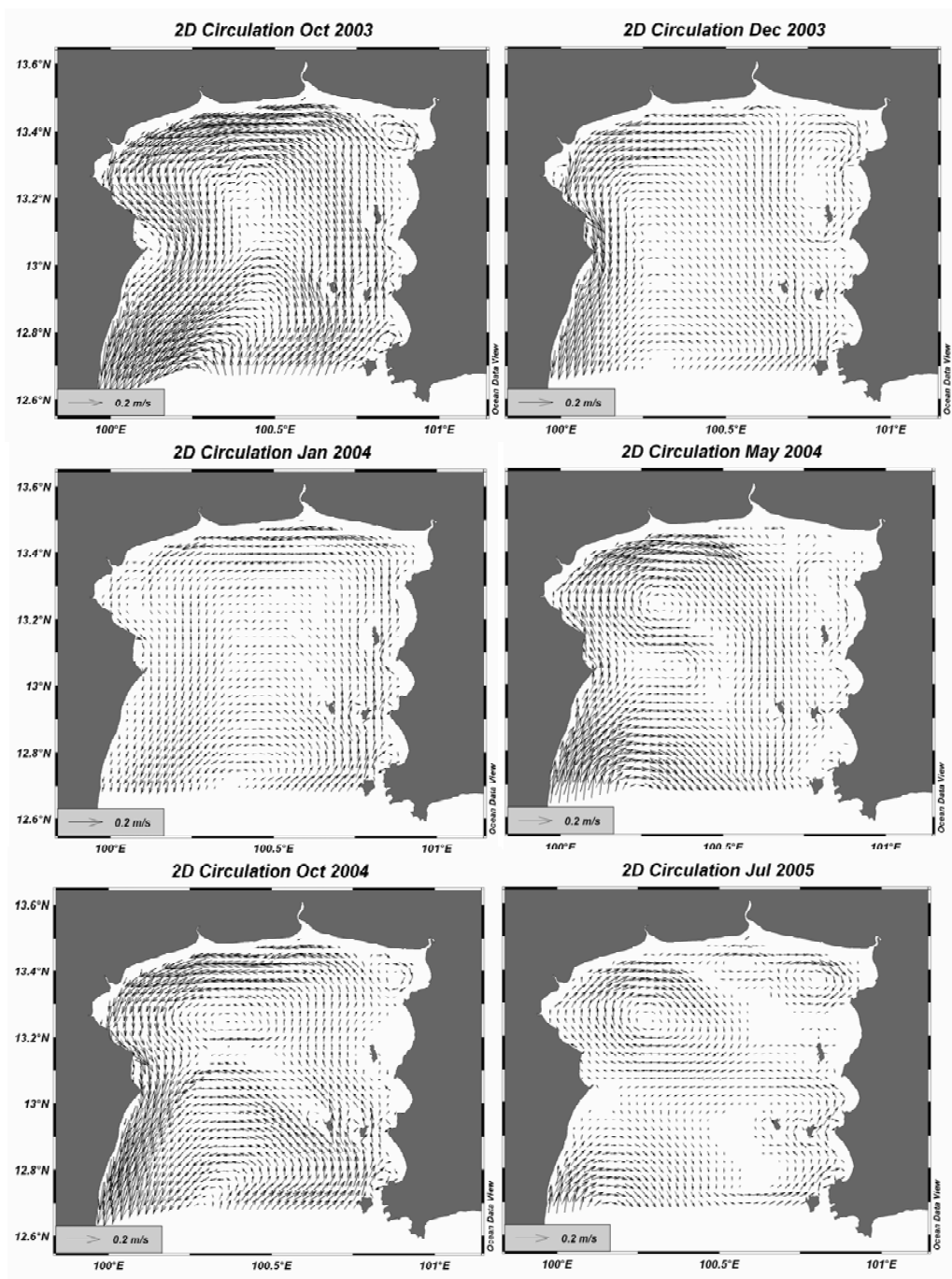
months except December 2003. Maximum elevation approaching 4-5 cm occurred in May 2004 when strong southwest winds pushed water to rise at the northeastern corner of the gulf. Only in December 2003 was the elevation lower than mean sea level because surface water was pushed out of UGoT following north-northeastern winds.



**Figure 6** Monthly mean water levels, simulated using POM, in the same months of observational cruises.

Circulation patterns are clearly seen in the case of vertically averaged currents (Figure 7). Counter-clockwise circulation developed when the east winds (the northeast or the southeast) prevailed over the area in October 2003 and 2004, and December 2003 and January 2004, while a complete counter-clockwise gyre near the northern coast was formed in October 2004. Circulation patterns were

reversed, and more complicated, under the influence of the southwest winds in May 2004 and July 2005. A large clockwise circulation developed in the northwest, while numerous eddies were seen dispersing throughout the eastern portion of UGoT. Water in this season moved into, and out of, the area through the west and the east of the sea boundary, respectively.

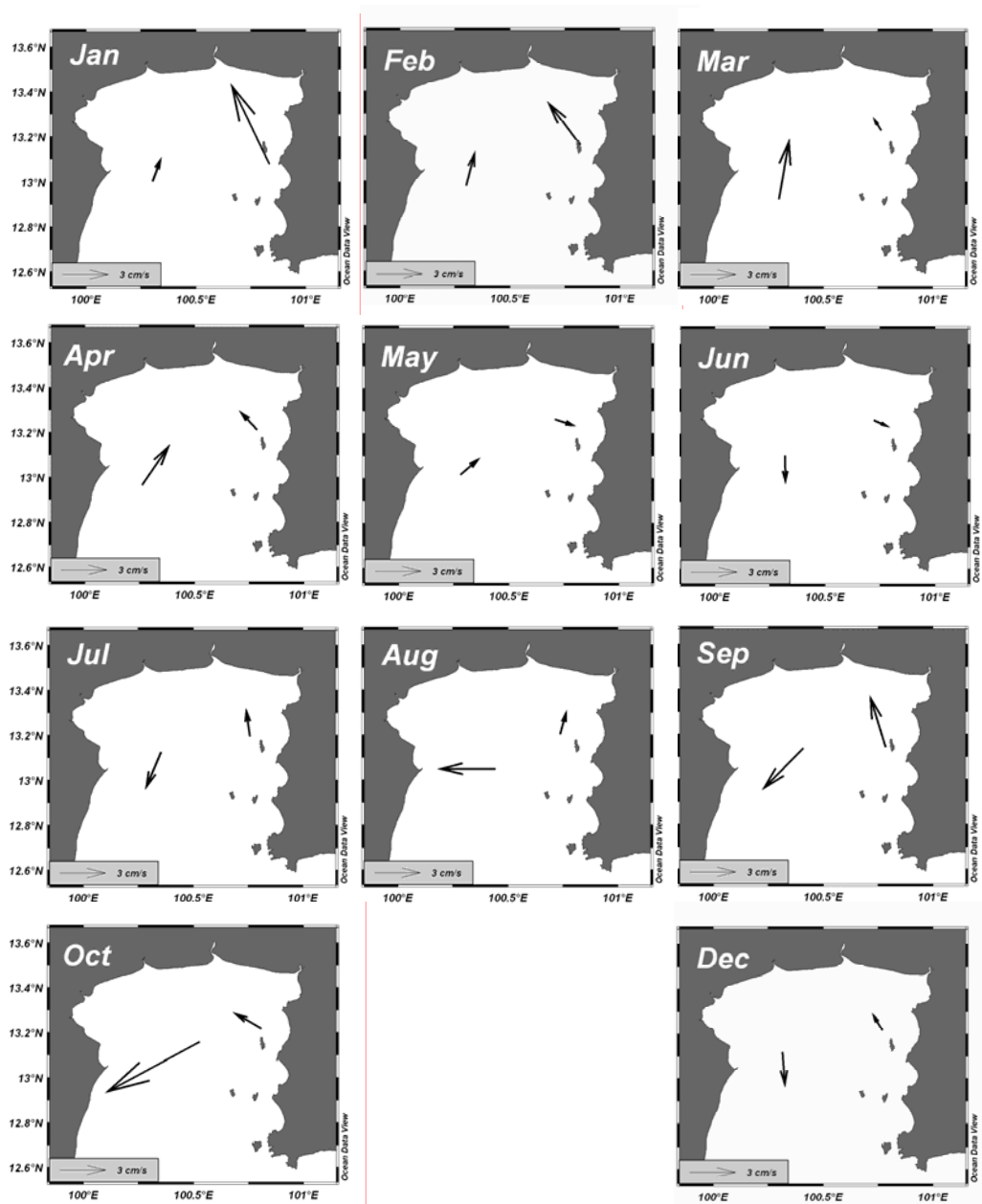


**Figure 7** Simulated depth-averaged circulation in the same months of observational cruises.

## 5. Result verification and discussion

Simulated current patterns were verified with the results of residual currents reported in Booncherm (1999), retrieved by filtering high frequency tidal influences out of instantaneous currents measured by two SEAWATCH buoys deployed in UGoT during 1996-1998. These residual currents were redrawn in a series of current plots for

each month of the year (Figure 8). The figure does not include the results from November due to data unavailability. Because buoy sensors were installed at the depth of about 3-5 m, surface current patterns were mainly used with contributions of the results at 10 m depth (Figure 4a to 4b) for verification purposes.



**Figure 8** Mean monthly surface circulation during 1996-1998 derived from data measured by SEAWATCH Thailand's buoys (Booncherm, 1999).

Most simulated results agree well with measured values in terms of surface inflows and outflows, and circulation patterns. However, discrepancies are observed in the case of July when both results indicate opposite trends of circulation, clockwise and counter-clockwise for simulated and measured results, respectively. Possible explanations for this difference include year-to-year variations of wind fields, the interaction of water from the central GoT, discharge-induced circulations and imbalance of bottom topography. In general, if uniform wind blows from the southwest, clockwise-circulation will be generated. In the case of non-uniform wind fields, if wind curl is positive, counter-clockwise circulation might be a consequence. These conditions happen when wind speeds from the east or south are stronger than those from the west or north, respectively (Buranapratheprat et al., 2006). The study also suggested that if there is a strong flow coming through the eastern sea boundary (Buranapratheprat and Bunpapong, 1998) in the same time, the possibility of counter-clockwise development will increase. With regard to discharge, freshwater from rivers located in the north might induce surface flow to the west of UGoT following Coriolis effect. Such flow may be strong enough to induce counter-clockwise circulation especially in wet season. Lastly, bottom topography may also contribute to this circulation pattern since the water depth along the eastern coast is deeper than that in the west. Induced by tide, larger water volume intruding from the south in the east of UGoT may result in a positive curl of residual circulation. All of these issues are very interesting and need to be the focus of future investigation.

## 6. Conclusion

POM was used to investigate seasonal circulation patterns in UGoT which were found to change due mainly to influences from seasonal winds. Intrusion of surface water through the sea boundary in the east and the west corresponded to wind fields blowing from the same directions. Water pile-up occurred when wind directed

landward, or to the north, in almost every month of the experiments. Only in December 2003 were there winds that flowed to the south resulting in the monthly average water level to be lower than annual-mean sea level. Water in deeper layers attempted to self-adjust to the movement of surface water and characteristics of bottom topography. This phenomenon corresponded to vertical circulation that revealed upwelling and downwelling owing to divergence and convergence conditions at the sea surface, respectively. Circulation patterns in UGoT were clearly seen in the case of vertically averaged current results. Clockwise and counter-clockwise patterns were developed during the influences of the southwest and the northeast winds, respectively. Comparisons of two-dimensional circulation results with those of a previous investigation showed some discrepancy as a consequence of the water pile-up effect. Model validation indicated that general circulation patterns agreed well with observations. Reverse circulation between observed and computed results in July were possibly due to interannual variations in wind patterns, interaction of water from the central GoT, influence from river discharge, or bottom topography.

## Acknowledgement

The authors would like to thank Dr. Mark Flaherty from Department of Geography, University of Victoria for his support.

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