Continental Shelf Research 28 (2008) 2509–2522

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Seasonal variation in water column conditions in the upper Gulf of Thailand

Anukul Buranapratheprat [a,*], Tetsuo Yanagi [b], Satsuki Matsumura [c]

[a] Department of Aquatic Science, Faculty of Science, Burapha University, T. Saensuk, A. Muang, Chonburi 20131, Thailand
[b] Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan
[c] Department of Marine Science, Chulalongkorn University, 254 Phayathai Road, Bangkok 10330, Thailand

A R T I C L E I N F O

Article history:
Received 30 October 2007
Received in revised form
21 April 2008
Accepted 15 July 2008
Available online 24 July 2008

Keywords:
Water column analysis
Temperature and salinity distributions
Gulf of Thailand

A B S T R A C T

Seasonal variation in water column conditions in the upper Gulf of Thailand (UGoT) was analyzed by considering four major factors including surface heat flux, freshwater discharge, tidal and wind stirrings. The coincidence of surface heat loss, low river discharge and strong wind resulted in vertical well-mixing in December. Strong stratification developed in September and October due to large river discharge and moderate heat flux. Strong surface heating in April and May has a potential to generate strong stratification, although not as large as that in September and October due to low river discharge. Although no factors are prominent during January and March, and June and August, weak to moderate stratification results, because the influences of river discharge and surface heating are still larger than those of tidal and wind stirrings. The results of water column analysis based on monthly average data agree well with analyses derived from cruise data in the same months. Most analytical results correspond to the distributions of temperature and salinity from field observations. Disagreement, however, was found in December 2003 (cruise CU-2) when stratification in some small regions occurs in the distribution of water properties, but the water column analysis suggests vertical well-mixing. This phenomenon is triggered by non-uniform distribution of freshwater over UGoT, which is related to river discharge, monsoonal wind and current. Compared to a previous study regarding surface chlorophyll dynamics, water column conditions may be used to explain the occurrence of phytoplankton bloom in this region.

1. Introduction

Mixing and stratification of the water column in a coastal sea are typically controlled by several factors including surface heat flux, wind stress and tidal stirring. In a region of freshwater influence (ROFI), interaction of the controlling factors on water column condition is more complex resulting from the contribution of freshwater discharge or runoff (Simpson, 1997). Generally in the tropical zone, surface heat flux and freshwater discharge strengthen vertical stability, while tide and wind stress increase water mixing and turbulence (Yanagi et al., 2001). These factors are also modified by topographic features in each area. It is, therefore, necessary to understand these controlling factors and their roles in order to explain the mechanism of water column variability in the area of interest.

Before transported farther to the open sea, freshwater-borne contaminants in both dissolved and particulate forms enter ROFIs. These contaminants such as pesticides (Tanabe et al., 1991), trace metals (Guieu et al., 1998) and nutrients were found to accumulate in these areas. Regarding eutrophication, land-derived inputs frequently maintain high nutrient concentrations in ROFIs, increasing primary productivity and massive algal blooms (Simpson, 1997). Hypoxia and, in some cases, toxins, generated by blooming species, potentially cause severe consequences to coastal ecosystems. Organic substances, carried down by freshwater, worsen this eutrophic condition by consuming high levels of dissolved oxygen in the water column through decomposition. Such serious water quality deterioration sometimes results in massive mortality of marine life in surrounding areas.

The upper Gulf of Thailand (UGoT), a shallow coastal sea located in a tropical area centered at latitude 13°N and longitude 100°30′E (Fig. 1), has characteristics like an ROFI due to freshwater influence. This area has a square-like shape, bordered by land in eastern, northern and western sides. Only the southern boundary opens to the main Gulf of Thailand (GoT). UGoT has an average depth about 20 m, with a maximum depth of 40 m located in the southeastern area. The entire GoT is under the influence of the dry northeast (November–January) and the wet southwest (May–August) monsoons. Strong seasonal variations in precipitation and

* Corresponding author. Tel.: +66 38 102222x3094; fax: +66 38 393491.
E-mail addresses: anukul_bu@hotmail.com, anukul@buu.ac.th (A. Buranapratheprat), tyanagi@riam.kyushu-u.ac.jp (T. Yanagi), satsuki_tomiko@hotmail.com (S. Matsumura).

0278-4343/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2008.07.006

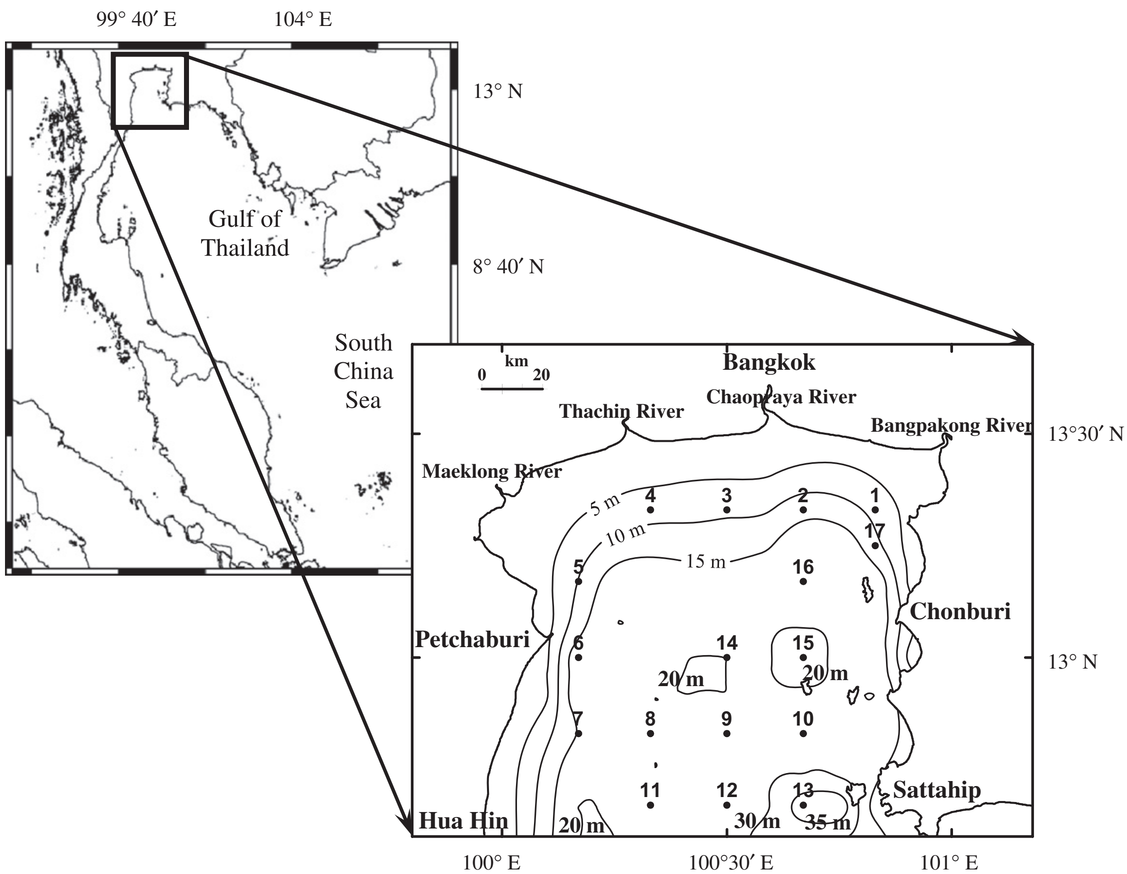

Fig. 1. The upper Gulf of Thailand, indicating depth contour (m) and oceanographic station (dots).

river discharge result, and this, together with other controlling factors, leads to seasonal variations in water column conditions. To date, the details of water column conditions and their relationship to the controlling factors in this region have not yet been investigated. Yanagi et al. (2001) reported the seasonal variations in water stratification in the whole GoT, but they did not take UGoT into consideration.

Based on simulated results by using a coupled circulation–ecosystem model applied for UGoT, Buranapratheprat et al. (2008) found a relationship between phytoplankton bloom and water column stability. Surface chlorophyll-*a* (chl-*a*) significantly increased where upwelling develops or vertical diffusion is low due to weak wind speed or freshwater buoyancy inputs. Such condition strengthens water stability, which allowed phytoplankton cells to accumulate near the sea surface and bloom. The model results also suggested the mechanism of a condition of "high nutrients, low chlorophyll" in the area as a consequence of strong vertical diffusion. This alternative aspect might be used to explain the mechanism of phytoplankton blooms in the area. The objectives of the present study are, therefore, not only to clarify the seasonal variations in water column conditions and the controlling mechanisms, but also to discuss the relationship between these physical properties and chl-*a* signatures within the area.

2. Observations and data sources

Temperature and salinity profiled data from field observations (Matsumura et al., 2006), used to analyze the water column condition, were measured in situ utilizing a CTD in 16–17 stations covering the UGoT area (Fig. 1). There were six cruises altogether starting from October 2003 (CU-1) to July 2005 (CU-6) (Table 1). Wind data were derived from QuickScat (http://www.ssmi.com). Due to unavailability of surface heat flux data at the same time of the experiments, long-time averaged data (1992–2001 for short wave radiation, 1990–1999 for long wave radiation, 1991–1995 for sensible heat flux and 1992–2000 for latent heat flux) were applied. The surface heat flux data (Fig. 2) were provided by the School of Marine Science and Technology, Tokai University, available through http://dtsv.scc.u-tokai.ac.jp/j-ofuro/.

Table 1
List of observational cruises for oceanographic data collection

Cruises	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	26–29 July 2005

3. Water column condition: monthly analysis

Tide-induced mixing is estimated by using the Simpson–Hunter parameter (Simpson and Hunter, 1974), defined as

$$\chi = \frac{H}{U_t^3} \quad (1)$$

where H is the water depth (m) and U_t is the averaged tidal current speed (m s^{-1}). According to Stansfield and Garrett (1997),

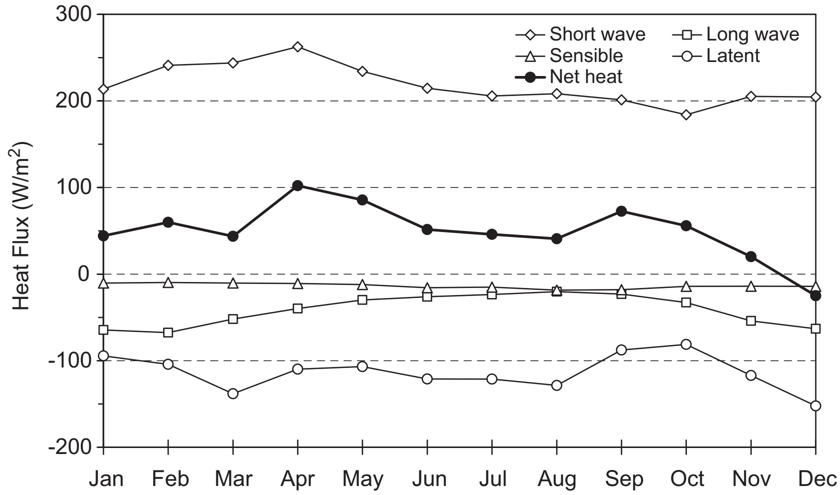

Fig. 2. Averaged monthly surface heat flux over UGoT (*source*: http://dtsv.scc.u-tokai.ac.jp/j-ofuro/).

the critical value of χ for vertical mixing in mid-latitudes is about $100\,s^3\,m^{-2}$. Substituting $\chi = 100\,s^3\,m^{-2}$ and $U_t = 0.2\,m\,s^{-1}$ (Buranaprathepra, 2000) in Eq. (1) yields $H = 8\,m$. This estimation suggests that stratification be dominant in this area, where the average depth is about 20 m. The influence of tidal stirring is strong enough to generate vertical well-mixing in the water column, where water depth is shallower than 8 m.

The mean rate of change of potential energy of water column (dV/dt) (Eq. (2)) is applied to evaluate the water column condition (stratified or vertically mixed) (Simpson and Bowers, 1981). Four significant environmental factors including surface heating, freshwater input, tidal and wind stirrings are taken into consideration:

$$\frac{dV}{dt} = -\frac{\alpha g Q H}{2C_p} - \frac{\beta g S H R}{2A} + \frac{4\varepsilon k_b \rho_w U_t^3}{3\pi} + \delta k_s \rho_a W^3 \quad (2)$$

The first and the second terms represent the influences of surface heating and freshwater input, and the third and the fourth terms stand for the effects of tidal and wind stirrings, respectively. The potential energy (V) is relative to the mixed condition (Simpson and Bowers, 1981); therefore, positive and negative signs are correspondingly assigned to the terms that increase and decrease vertical water column mixing. All constants together with their definitions, values and units are summarized in Table 2. It should be noted that the surface drag coefficient was treated as a constant in several studies (e.g., Simpson and Bowers, 1981; Yanagi et al., 2001), but it was considered as a variable in the present study due to its sensitivity to wind magnitude (Stewart, 2006). The estimations, based on the relationship between wind magnitude at 10 m above sea surface (W_{10}) and surface drag coefficient (C_D) (Yelland and Taylor, 1996) were employed:

$$1000C_D = 0.29 + \frac{3.1}{W_{10}} + \frac{7.7}{W_{10}^2} \quad (3 \leqslant W_{10} \leqslant 6\,m\,s^{-1}) \quad (3a)$$

$$1000C_D = 0.60 + 0.071\,W_{10} \quad (6 \leqslant W_{10} \leqslant 26\,m\,s^{-1}) \quad (3b)$$

The bottom drag coefficient is also dependent on environmental factors such as current velocity, bottom substrate and water depth. Due to uncertainty in the methods of estimation and reported values (e.g., Sternberg, 1968; Spitz and Klinck, 1998; Li et al., 2004), the coefficient was applied in the calculation as a constant (0.0025), which has been used in many numerical models including the Princeton Ocean Model (POM) (Mellor, 1998).

Table 2
Parameters used for the calculation of the rate of change of potential energy in water column

Symbols	Definitions	Values	Units
α	Thermal expansion coefficient	2.3E−04	$°C^{-1}$
g	Gravitational acceleration	9.8	$m\,s^{-2}$
H	Water depth		m
Q	Heat flux		$W\,m^{-2}$
C_p	Specific heat of water	0.95	$Cal\,g^{-1}\,°C^{-1}$
β	Salinity contraction to density	0.001	$g\,cm^{-3}\,psu^{-1}$
S	Salinity		psu
R	River discharge		$m^3\,s^{-1}$
A	Surface area under river discharge influence		m^2
ε	The efficiency of conversion from turbulence to potential energy for tidal stirring	0.015	
k_b	Bottom drag coefficient	2.5E−03	
ρ_w	The density of seawater	1.02	$g\,cm^{-3}$
U_t	Tidal magnitude		$m\,s^{-1}$
δ	The efficiency of conversion from turbulence to potential energy for wind stirring	0.039	
C_D	Surface drag coefficient (Eqs. (3a) and (3b))		
k_s	$C_D \times \gamma$		
γ	The ratio of wind-induced current to wind speed	0.0127	
ρ_a	The density of air	1.25E−03	$g\,cm^{-3}$

Monthly average dV/dt was calculated to investigate seasonal variations in water column condition in UGoT. Averaged monthly data of heat flux (Fig. 2), river discharge and wind magnitude (Fig. 3) for the entire year were taken into consideration. Other parameters assigned included H of 20 m, A of $10^4\,km^2$ and U_t of $0.2\,m\,s^{-1}$. Due to lack of salinity data, it was, therefore, assumed to be 30 psu in every month. The results of seasonal variations in total dV/dt values and their components are illustrated in Fig. 4.

Stratified water conditions are expected in all months except in December due to surface heat loss, low river discharge and high wind speed. Coincidence between large river discharge and moderate surface heating results in strong stratification in September and October. Although surface heat input is largest in April and May, it cannot maintain stratification in magnitudes as strong as that in September and October due to low river discharge. During January and March, and June and August, weak to moderate stratification develops from the influences of river discharge and surface heating being still larger than those of tidal and wind stirrings.

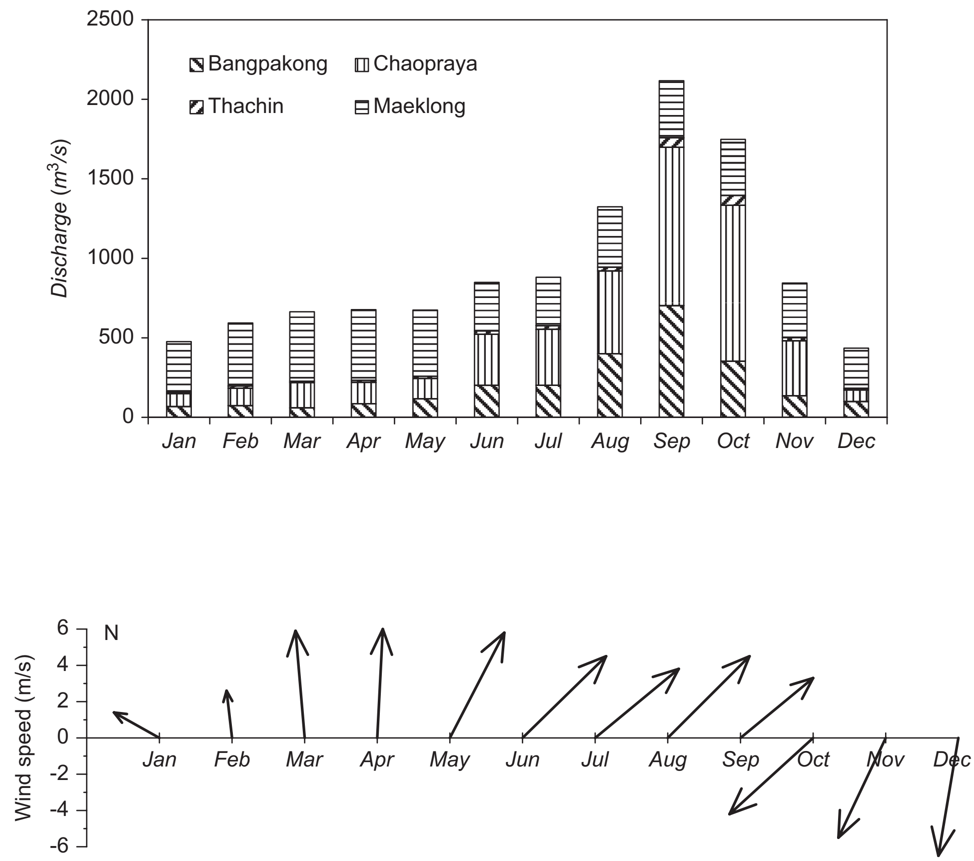

Fig. 3. Average monthly river discharges into UGoT (upper panel) (source: the Royal Irrigation Department of Thailand) and averaged monthly wind vectors over UGoT (lower panel) (*source*: http://www.ssmi.com).

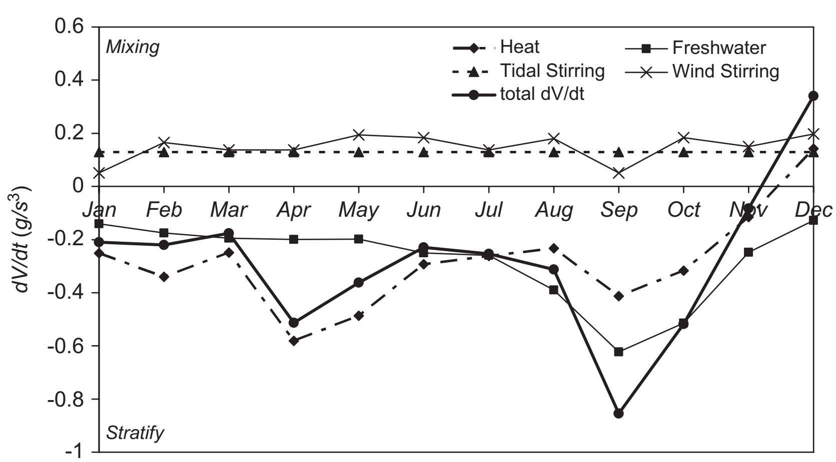

Fig. 4. Seasonal variations in the rate of change of potential energy in the water column in UGoT.

4. Distributions of temperature and salinity

Horizontal distributions of sea surface temperature and salinity of all cruises are illustrated in Figs. 5 and 6, respectively. Seasonal changes in surface temperature limited ranges for 26 °C in January and 31 °C in May 2004, following the seasonal temperature in local wintertime and summertime. Low salinity of 16–17 psu appeared close to the western shoreline in October 2003, while the maximum value of about 33–34 psu was observed near the mouth of UGoT in July 2005. These phenomena were clearly controlled by seasonal variability in the amount of freshwater discharges (Table 3) and also water stratification (more discussion is presented in the last paragraph of this section). The salinity gradient (7–9 psu) of horizontal distributions from the northern coast toward the sea boundary was largest in October of both years. Temperature did not show such distinction and its spatial difference greater than 1 °C was infrequently seen in any observation across UGoT.

Horizontal distributions of both temperature and salinity also reveal seasonal changes in contour patterns that might be related to local circulation and interaction with water from the main GoT. Temperature contours in the northern area trended to the west or

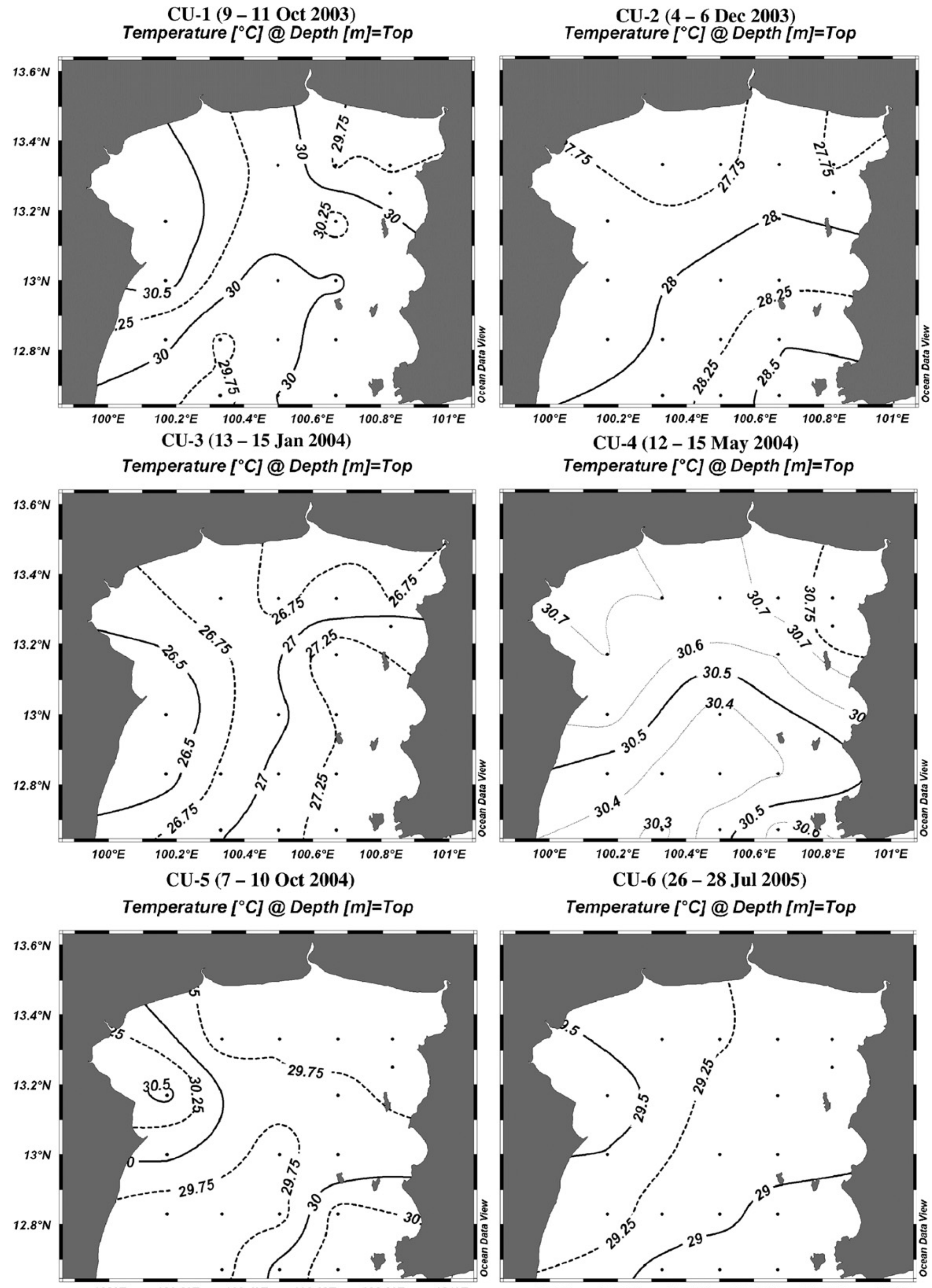

Fig. 5. Horizontal distributions of sea surface temperature of all cruises.

counter-clockwise in October 2003 and 2004, January 2004 and July 2005 (Fig. 5). The trends of temperature distribution in other months are unclear. Movement trend of salinity distributions can be found in every cruise. Contours in the central and northern areas bended to the west in October 2003 and 2004, December 2003 and January 2004, while those in May 2004 and July 2005 clearly moved northeastward (Fig. 6). Movement of surface salinity contours agrees well to seasonal mean flows investigated using a two-dimensional model (Buranapratheprat et al., 2002) indicating the development of clockwise and a counter-clockwise circulations over UGoT during the southwest and the northeast monsoons, respectively.

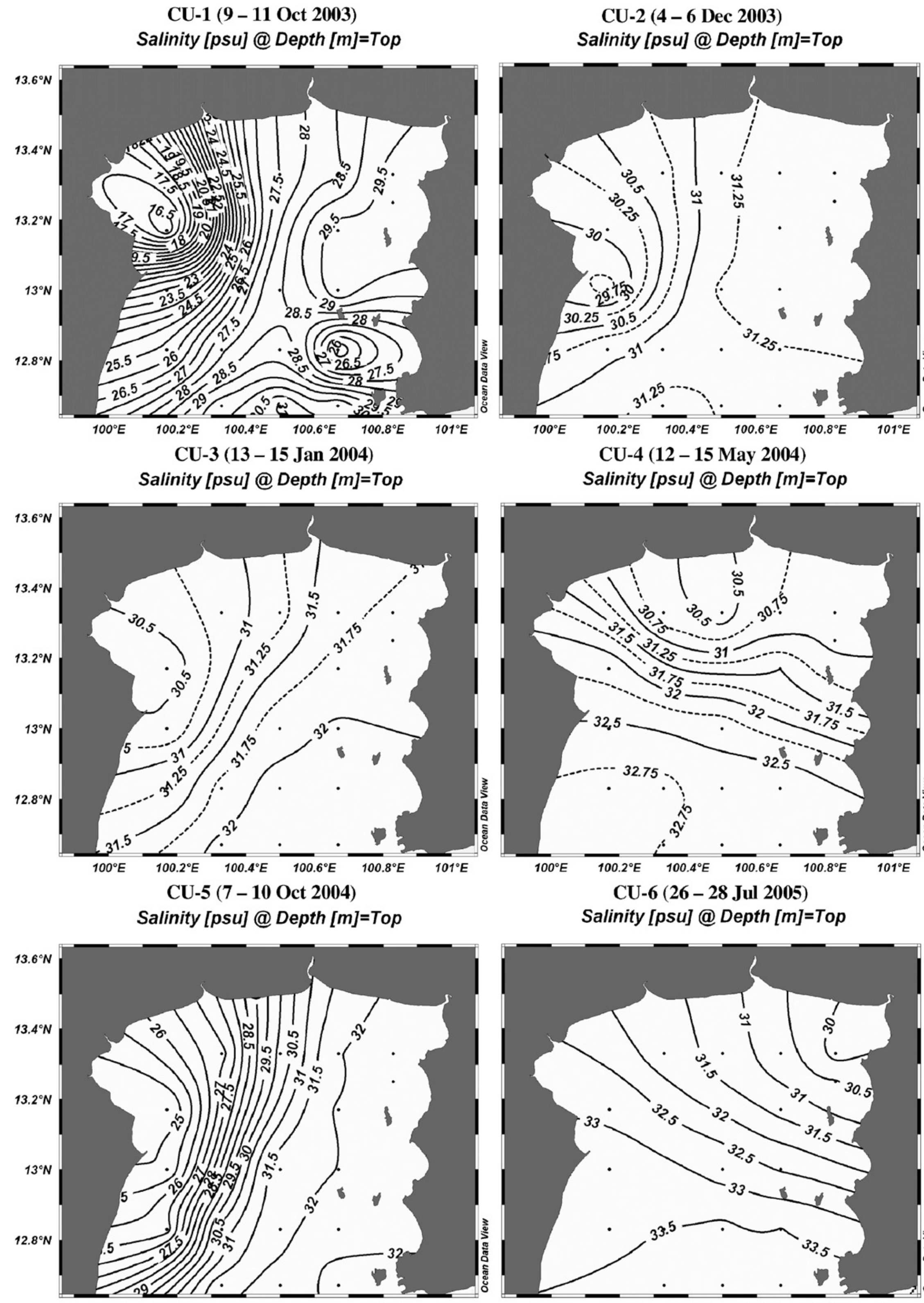

Fig. 6. Horizontal distributions of sea surface salinity of all cruises.

Vertical distributions of temperature and salinity data (Figs. 7 and 8) are used to investigate seasonal variations in water stratifications. Both parameters from stations located in the same latitude (Fig. 1) were averaged to represent points along the north–south axis. This consideration was applied instead of using data from any longitudinal line because of non-uniform distribution of river discharge over the UGoT area. It should be added that salinity is the most influential control of water density in this area, compared to temperature; therefore, both salinity and density distributions can be referred to each other (Buranapratheprat and

Table 3
Parameters used for the calculation of the rate of change of potential energy in water column during cruise periods

Variables	Cruises					
	CU-1 October-03	CU-2 December-03	CU-3 January-04	CU-4 May-04	CU-5 October-04	CU-6 July-05
Salinity (S) (psu)	27.6	31	31.6	32	30.3	32.5
River discharge (R) (m^3 s)	2,730	594	550	652	1,792	572
Surface heat flux (Q) (W m^{-2})	55.77	−24.92	44.16	85.55	55.77	45.89
Wind magnitude (W_{10}) (m s^{-1})	5.0	7.3	3.1	5.3	4.9	6.4
Surface drag coefficient (C_D)	5.98E-04	1.11E-03	1.09E-03	5.61E-04	6.11E-04	1.05E-03
k_s ($C_D \times \gamma$)	7.6E-06	1.42E-05	1.39E-05	7.13E-06	7.76E-06	1.34E-05
Tidal magnitude (U_t) (m s^{-1})	0.2	0.1	0.2	0.3	0.3	0.2

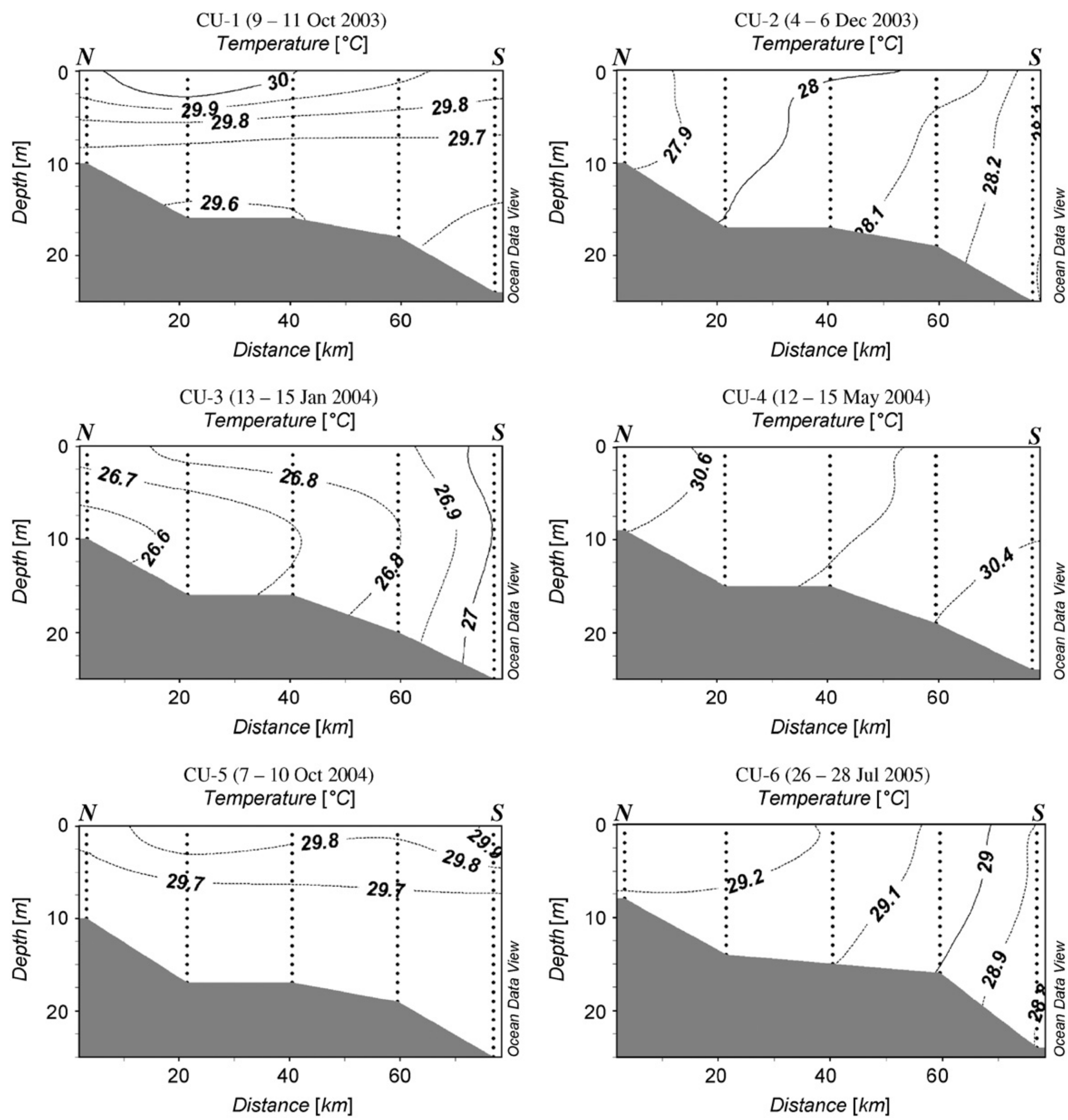

Fig. 7. Vertical distributions of latitudinal-averaged temperature along the north–south direction.

Yanagi, 2003). The distributions in October 2003 and 2004 clearly show a stratified-like contour, while those in other months perform a partially mixed pattern. Vertical distributions of both temperature and salinity suggest strong stratification in October 2003 and 2004, moderate stratification in January 2004, May 2004 and July 2005, and moderately well-mixing in December 2003.

Seasonal changes of water masses in the study area are investigated through the use of a temperature–salinity (T–S) diagram (Fig. 9). Movement of scatter plots along temperature and

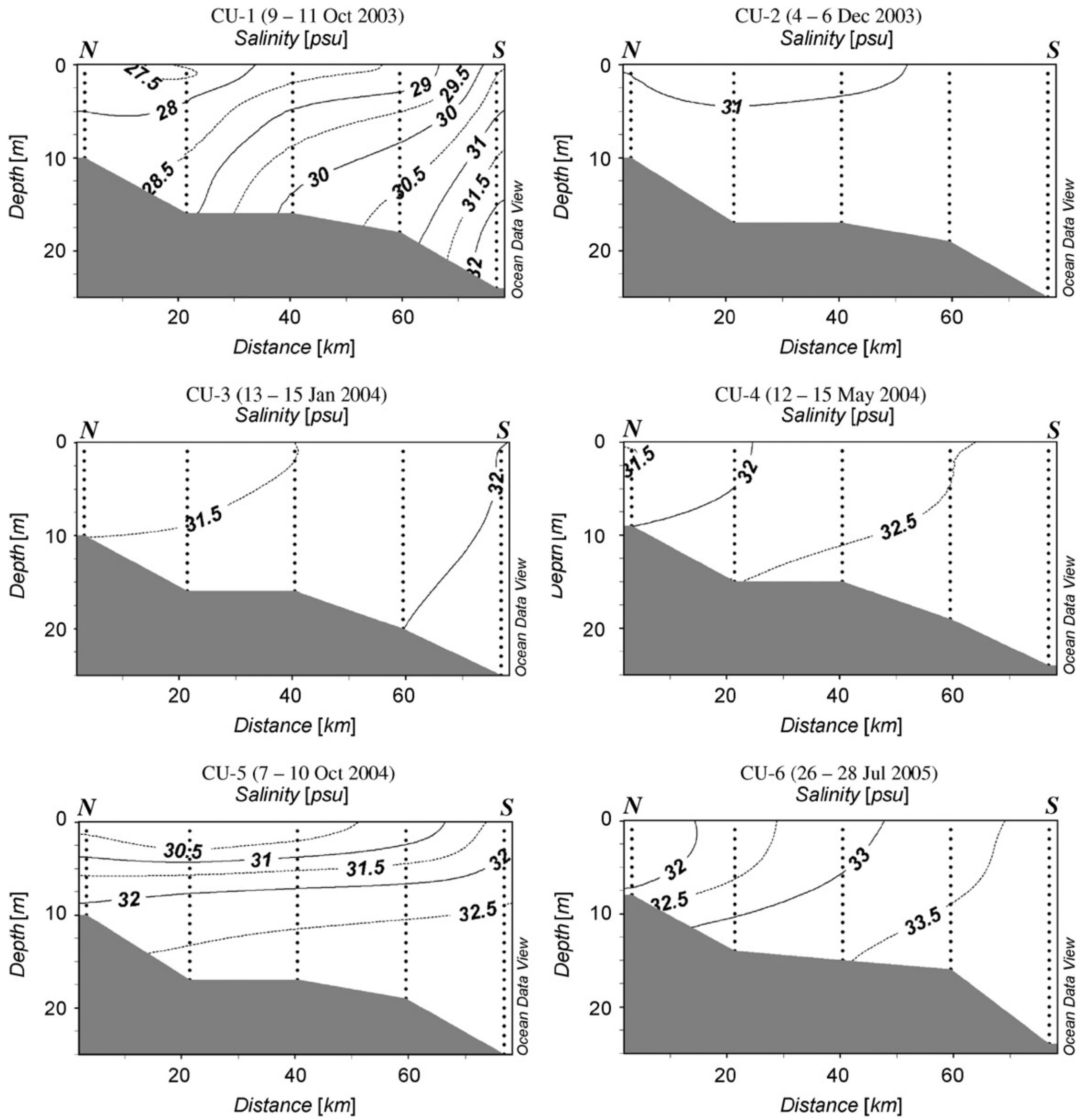

Fig. 8. Vertical distributions of latitudinal-averaged salinity along the north–south direction.

salinity axes reflects seasons and seasonal variations in freshwater influence, respectively. Small temperature ranges of 3–4 °C were observed in all periods. This may be due to the tropical location and small study area. The salinity gradient was very large in October 2003 (CU-1) and October 2004 (CU-5) and small in December 2003 (CU-2) and January 2004 (CU-3). These phenomena are explained by seasonal variations in river discharges emptying into the head of UGoT (Table 3)—larger discharges always create higher salinity gradients.

Vertical distributions of salinity and *T*–*S* diagram disclose the influence of high salinity (32–33.5 psu) intrusion from the main GoT in all seasons. Stratification, however, also played a significant role in controlling salinity in the water column. This is observed by comparing the results of January 2004 and July 2005. Maximum salinity emerged in the latter, not the former, although discharges in both months were almost the same (Table 3). A well-mixed condition was responsible for seawater dilution in January 2004. The same amount of freshwater inputs, instead of being mixed, floated over the higher salinity water, while moving seaward in July 2005. Salinity of the near seafloor water was still high due to the development of stratification in this time.

5. Water column condition: cruise analysis

Water column condition during all six cruise periods were analyzed following Eq. (2) with the use of parameters in Tables 2 and 3. Salinity data were derived from averaged data over the entire area of each cruise. Discharge data and wind magnitude resulted from weekly averaged data in the same time of the cruises. Due to data unavailability, the average monthly surface heat fluxes were still used in this analysis. Spring and neap tides were taken into consideration for tidal magnitudes during cruise periods. They were estimated from tidal data presented in Buranapratheprat (2000). Tidal magnitudes were assigned as $0.3\,m\,s^{-1}$ during spring tide (CU-4 and CU-5), $0.1\,m\,s^{-1}$ during neap tide (CU-2) and $0.2\,m\,s^{-1}$ during the transition between spring and neap tides (CU-1, CU-3 and CU-6).

Negative d*V*/d*t* in all cruises, but CU-2 (Table 4), suggests that stratification is dominant in UGoT, corresponding to the results of monthly water column analysis (Fig. 4). Strong stratification in October of both years (CU-1 and CU-5) was mainly controlled by large river discharge ($>1500\,m^3\,s^{-1}$) and moderate surface heating ($\sim 55\,W\,m^{-2}$). Smaller discharge and larger tidal

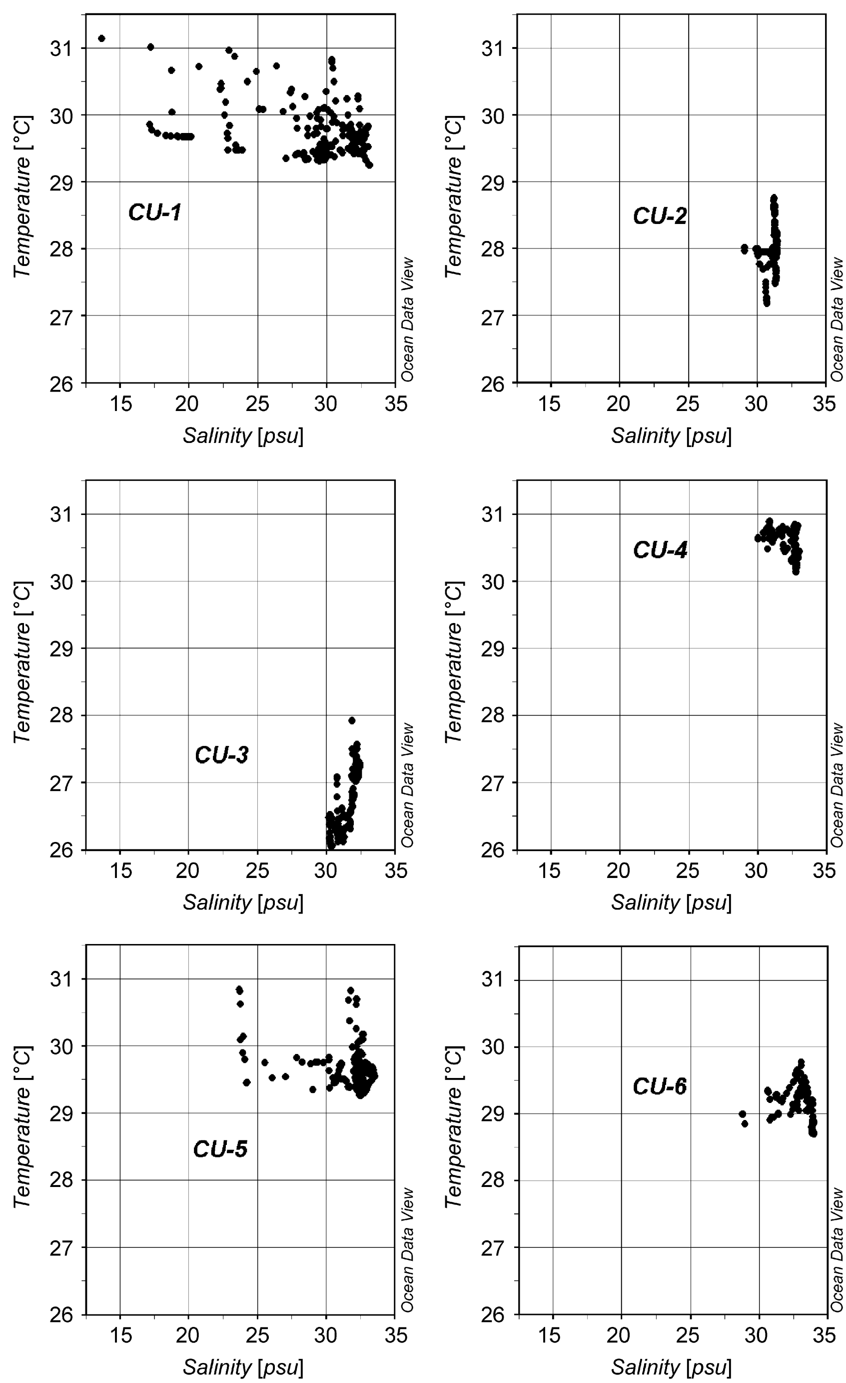

Fig. 9. *T–S* diagram of the data in each cruise.

Table 4
The rate of change of potential energy (d*V*/d*t*) in each cruise period

d*V*/d*t*	Cruises					
	CU-1 October-03	CU-2 December-03	CU-3 January-04	CU-4 May-04	CU-5 October-04	CU-6 July-05
Heat	−0.32	0.14	−0.25	−0.49	−0.32	−0.26
Freshwater	−0.74	−0.18	−0.17	−0.20	−0.53	−0.18
Total buoyancy	−1.06	−0.04	−0.42	−0.69	−0.85	−0.44
Tidal stirring	0.13	0.02	0.13	0.44	0.44	0.13
Wind stirring	0.05	0.26	0.02	0.05	0.04	0.17
Total stirring	0.18	0.28	0.15	0.49	0.48	0.30
Total	−0.88	0.24	−0.27	−0.20	−0.37	−0.14

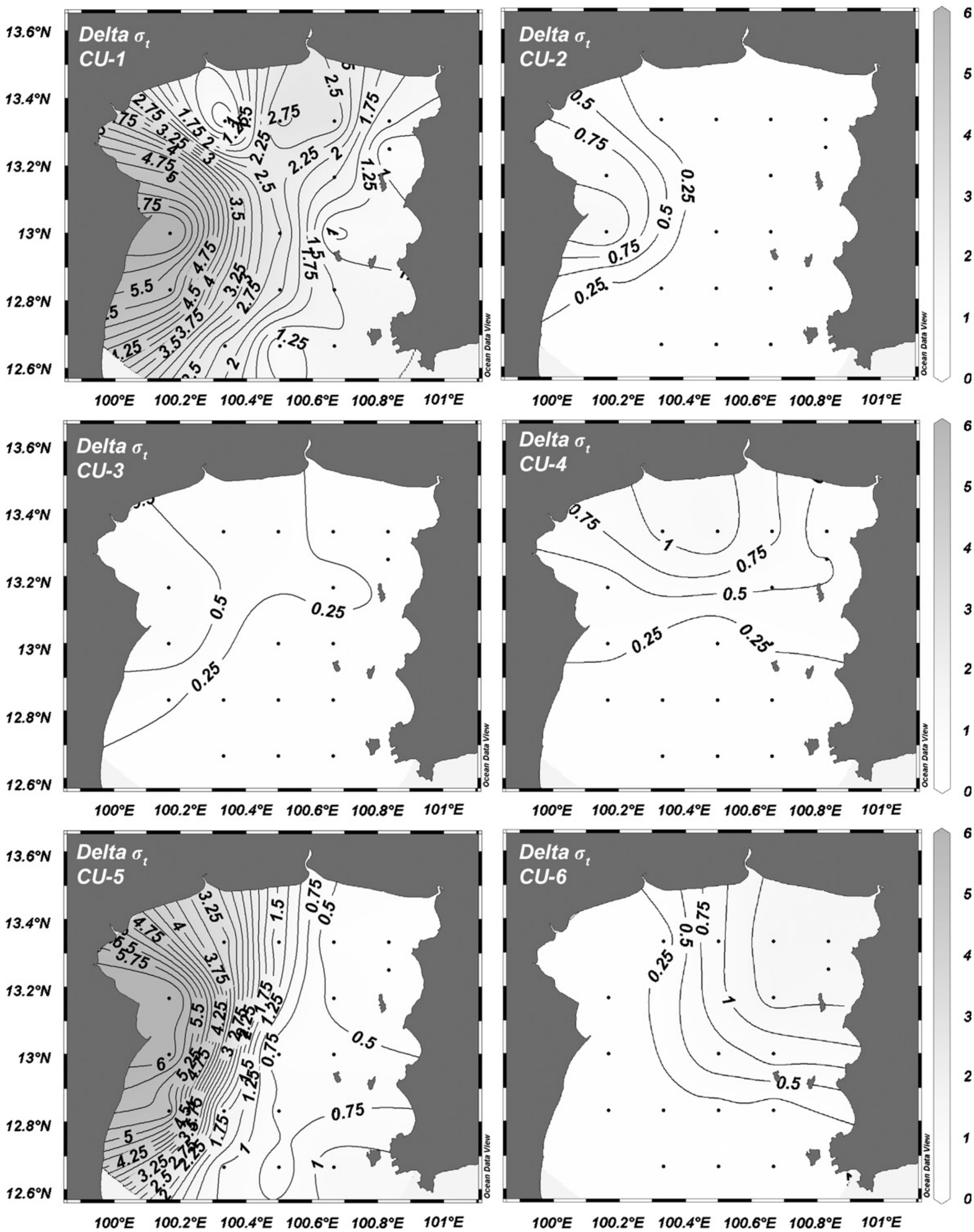

Fig. 10. Spatial distributions of surface–bottom density difference ($\Delta\sigma_t$) of all cruises.

magnitude are responsible for weaker stratification in October 2004 (CU-1), compared to October 2003 (CU-5). Stratification developed in May 2004 (CU-4) because of strong surface heating (85.5 W m^{-2}), although the discharge was less than a half of those in both Octobers. Wind magnitude, however, was also high during this time, but the total buoyancy (heat and freshwater) was larger than the total stirring (tide and wind), resulting in negative dV/dt (-0.2 g s^{-3}). dV/dt of -0.27 and -0.14 g s^{-3} in January 2004 (CU-3) and July 2005 (CU-6), respectively, also indicate water stratification trends. Stratification in both periods, however, may switch to vertically well-mixed conditions (+dV/dt) when tidal currents are strong during spring tide. This analysis suggests that water column condition in those periods is controlled by tidal cycle. Vertically well-mixing is expected in December due to positive dV/dt (0.24 g s^{-3}), resulting from surface heat loss, strong wind and low river discharge.

Estimated dV/dt agrees well with vertical distributions of temperature (Fig. 7) and salinity (Fig. 8) that stratification develops in most cruises. Disagreement is found in December 2003 (CU-2) when dV/dt resulted positive (0.24 g s^{-3}), but vertical distributions of temperature and salinity indicate weak stratification near the northern coast. The condition favored vertical mixing because of small discharge, surface heat loss and high wind magnitude. This issue is discussed in detail in Section 6.1.

6. Discussion

The results of monthly water column conditions in UGoT (Section 3) were compared to those of the entire GoT reported in Yanagi et al. (2001). Factors that might play a significant role to environmental alteration between both regions are the area of freshwater influence (10^4 and $3\times10^5\,km^2$ for UGoT and GoT, respectively) and mean water depth (20 and 40 m for UGoT and GoT, respectively). Both studies indicate that vertical mixing develops in winter (January and December). Strongest stratification, however, develops in different periods—April and September for GoT and UGoT, respectively. Large surface heat flux in April

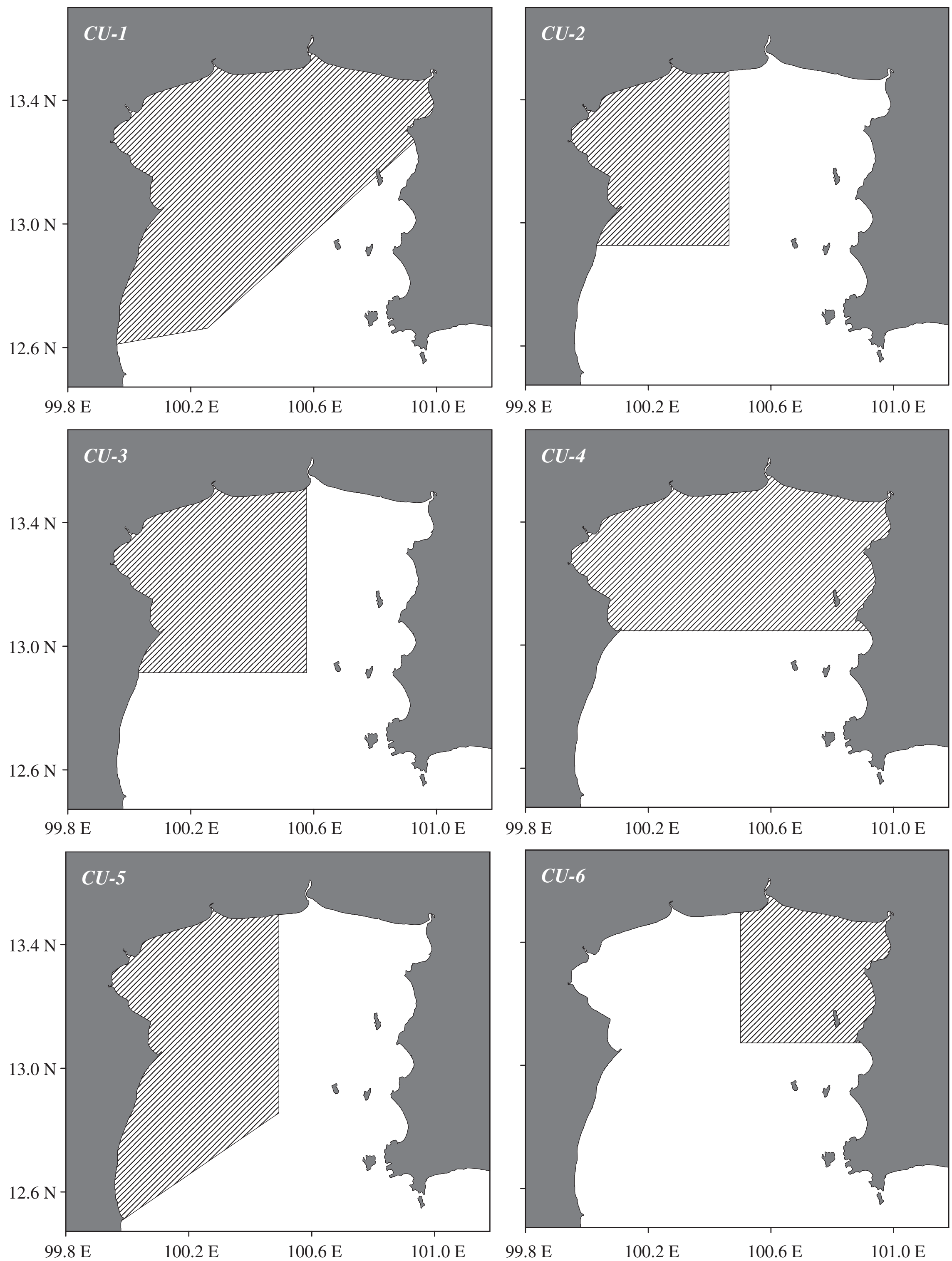

Fig. 11. Area of freshwater influence in each cruise period.

strengthens buoyancy flux and stratified water in GoT, but not in UGoT because tide-induced stirring is relatively large in shallow water (Eq. (2)). On the other hand, in September, freshwater discharge of 3000 $m^3 s^{-1}$ (Yanagi et al., 2001) cannot maintain strong stratification in GoT, where the area under freshwater influence is very large (3×10^5 km^2). This situation is different from UGoT, where just a small area of 10^4 km^2 received discharge over 2000 $m^3 s^{-1}$ in the wet season peak. Strong discharge influence and moderate surface heating are, therefore, responsible for strong stratification in UGoT in September.

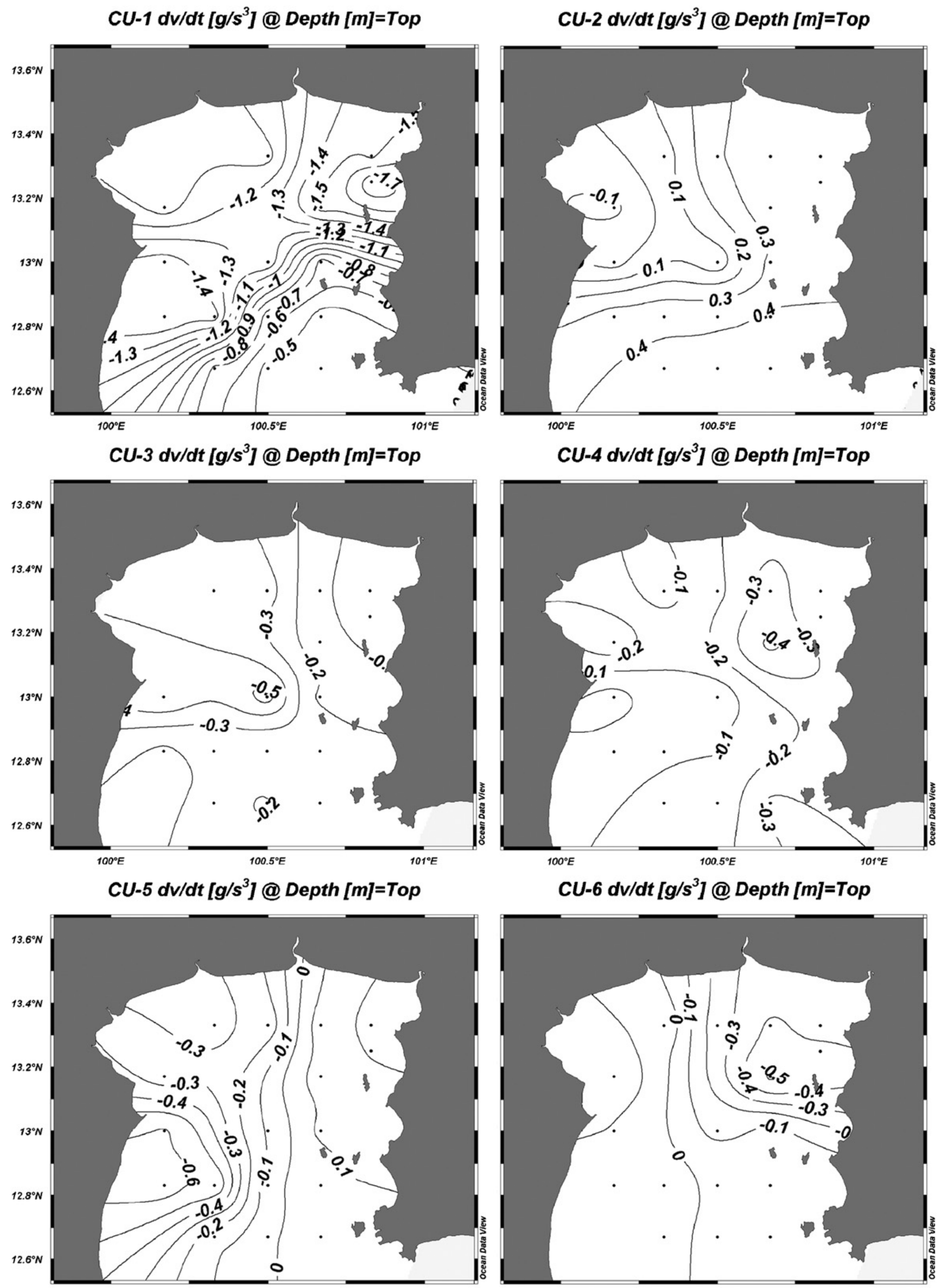

Fig. 12. Horizontal distribution of d*V*/d*t* in each cruise period.

6.1. Spatial distribution issue

One limitation of dV/dt estimation using Eq. (2) concerns the boundary of area under freshwater influence. The equation, which is one dimensional in nature, is based on a horizontal uniform distribution of all relevant factors. Surface heat flux, wind and tidal stirrings are usually uniform unless their spatial variations are very large. Unlike freshwater discharge, its horizontal distribution is usually non-uniform, due to lateral boundary properties, and Eq. (2) does not take this issue into consideration. This is the reason why dV/dt in December 2003 was positive ($0.24\,g\,s^{-3}$), while vertical distribution of salinity (Fig. 8) and horizontal distribution of surface–bottom density difference ($\Delta\sigma_t$) (Fig. 10) indicate weak stratification in the central west coast. The positive dV/dt result suggests that, if freshwater discharge is horizontal—homogeneously distributed, vertical well-mixing will be the consequence. This leads to the issue of spatial distribution of freshwater over the study area.

Station-by-station basis of dV/dt (Eq. (2)) was analyzed to investigate the influence of non-uniform distribution of freshwater on water column condition. The boundary of freshwater influential area in each cruise (Fig. 11) was assessed from the distribution of $\Delta\sigma_t$ (Fig. 10). The same dataset used for water column analysis during cruise periods (Section 5) are still employed, but they are separated for each station. The same values of surface heat flux, tidal and wind magnitudes are applied to all stations of each cruise, due to their small spatial distributions (Buranapratheprat et al., 2002, 2008). Numeric results were then plotted using ODV software to investigate the distribution of dV/dt and water column condition in the area.

Spatial distribution of dV/dt (Fig. 12) indicates trend of water stratification in all cruises, similar to the distribution of $\Delta\sigma_t$ (Fig. 10). The results also illustrate the relationship of spatial distribution of freshwater accumulation and water stratification. Their temporal movement seems to follow monsoonal wind and circulation reported in Buranapratheprat et al. (2002). Accumulation of freshwater, after discharged from rivers located along the northern coastline, occurs in the west and the east of UGoT following the northeast and the southwest monsoon, respectively. Stratification areas also move in the same way. This experiment shows that stratification in December 2003 (CU-2) can occur, although total dV/dt suggests mixing condition, due to non-uniform distribution of freshwater in UGoT. Since the environmental factors in this time of the year favor water mixing (Sections 3 and 5), this is the key point leading to the conclusion that water stratification in some parts of UGoT can develop year round, while its extend and location depend on seasonal variations in river discharge, wind and circulation.

6.2. Implication to phytoplankton production

Water column condition was found to be related to surface chl-*a* distribution in this shallow water area, where nutrients do not limit phytoplankton growth (Buranapratheprat et al., 2008). The simulation results using a coupled circulation–ecosystem model (Buranapratheprat et al., 2008) suggests that phytoplankton require water stability to initiate blooming. Phytoplankton population intensifies near the sea surface and then blooms when vertical diffusivity is low, related to weak wind, or upwelling. On the contrary, high vertical diffusivity, due to strong wind, and downwelling cause plankton cells to disperse throughout the water column, thereby inhibiting plankton cells to accumulate near the sea surface. Buoyancy input from river discharge also plays a minor role, because its influence is overwhelmed by wind-induced turbulence. Variation in wind magnitude and direction were used to explain year-to-year variation in surface chl-*a* between October 2003 (CU-1) and October 2004 (CU-5) (Fig. 13). Blooming along the western coast occurred in the former year because of weaker wind and stronger upwelling, although nutrients in the water column were similarly high and vertically uniform. Intense blooming in the same way as that of October 2003 could be reproduced when wind magnitude in October 2004 was decreased. The role of freshwater-induced stability, however, should not be ruled out since those results were derived from model simulations, not from field observations. The water column analysis from the present study suggests that the variability of freshwater inputs might significantly contribute to year-to-year variations because dV/dt (Table 4) and the horizontal distribution of $\Delta\sigma_t$ (Fig. 10) indicate stronger stratification in October 2003 than in October 2004. This topic requires further investigation in the future.

7. Conclusion

Seasonal variations in water column condition in UGoT were investigated by considering four forcing factors including wind and tidal stirrings, freshwater discharge and surface heat flux. Vertical well-mixing was predicted in December due to surface

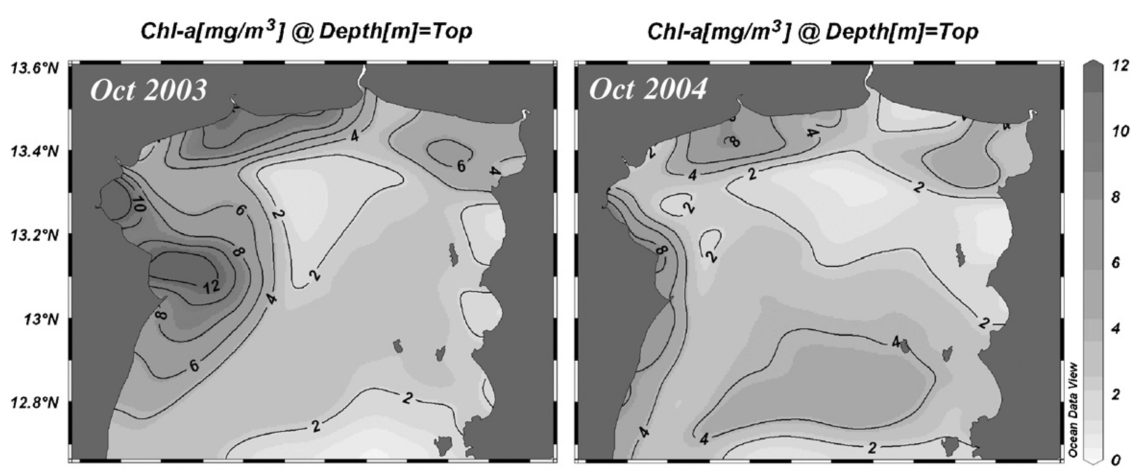

Fig. 13. Monthly average chl-*a* distribution at the sea surface in October 2003 and October 2004 simulated by a coupled circulation–ecosystem model (Buranapratheprat et al., 2008).

heat loss, high wind magnitude and low river discharge. Strong stratification is dominant in September and October because of large river discharge and moderate heat flux. Surface heating is very strong in April and May, but can maintain only moderate stratification due to low river discharge. No factors are prominent during January and March, and June and August. Weak to moderate stratification results in those months owing to the influences of river discharge and surface heating being larger than those of tidal and wind stirrings. Distributions of temperature and salinity, and water column analysis during cruise periods support the monthly average results that stratification is dominant in UGoT. Disagreement, however, was found in December 2003 (CU-2) when the distributions of water properties indicate weak stratification; however, the results of water column analysis suggests vertical well-mixing. This phenomenon was proved to be related to non-uniform distribution of freshwater over the area, which is controlled by river discharge, monsoonal wind and circulation. The results of this study and a previous investigation indicate that water column conditions might play a key role in phytoplankton dynamics in the area.

Acknowledgments

The authors would like to thank Dr. Pramot Sojisuporn from Chulalongkorn University for providing CTD data; Dr. Thaithaworn Lirdwitayaprasit from Chulalongkorn University for providing chlorophyll and nutrient data; Dr. Kashane Chalermwat from Burapha University for manuscript comments; The Royal Irrigation Department of Thailand for supporting river discharge data. We also thank the two reviewers for their comments and suggestions.

References

Buranapratheprat, A., 2000. Oil spill trajectory model testing in the upper Gulf of Thailand. In: Proceedings of the International Workshop on Environmental Sensitivity Index Mapping for Oil Spill in the Southeast Asian Seas, pp. 142–152.

Buranapratheprat, A., Yanagi, T., 2003. Seasonal variations in circulation and average residence time of the Bangpakong estuary, Thailand. La mer 41, 199–213.

Buranapratheprat, A., Yanagi, T., Sawangwong, P., 2002. Seasonal variation in circulation and salinity distributions in the upper Gulf of Thailand: modeling approach. Lamer 40, 147–155.

Buranapratheprat, A., Yanagi, T., Niemann, K.O., Matsumura, S., Sojisuporn, P., 2008. Surface chlorophyll dynamics in the upper Gulf of Thailand revealed by a hydrodynamic-ecosystem coupling model. Journal of Oceanography in press.

Guieu, C., Martin, J.-M., Tankere, S.P.C., Mousty, F., Trincherini, P., Bazot, M., Dai, M.H., 1998. On trace metal geochemistry in the Danube river and western black sea. Estuarine, Coastal and Shelf Science 47, 471–485.

Li, C., Valle-Levinson, A., Atkinson, L.P., Wong, K.C., Lwiza, K.M.M., 2004. Estimation of drag coefficient in James River Estuary using tidal velocity data from a vessel-towed ADCP. Journal of Geophysical Research 109.

Matsumura, S., Siripong, A., Lirdwitayaprasit, T., 2006. Underwater optical environment in the upper Gulf of Thailand. Coastal Marine Science 30 (1), 36–43.

Mellor, G.L., 1998. User's Guide for a Three-Dimensional, Primitive Equation, Numerical Ocean Model. Program in Atmospheric and Oceanographic Sciences Report, Princeton University, Princeton, NJ.

Simpson, J.H., 1997. Physical processes in the ROFI regime. Journal of Marine Systems 12, 3–15.

Simpson, J.H., Bowers, D., 1981. Models of stratification and frontal movement in shelf seas. Deep-Sea Research 28A (7), 727–738.

Simpson, J.H., Hunter, J.R., 1974. Fronts in the Irish sea. Nature 250, 404–406.

Spitz, Y.H., Klinck, J.M., 1998. Estimation of bottom and surface stress during a spring-neap tide cycle by dynamical assimilation of tide gage observations in the Chesapeake bay. Journal of Geophysical Research 103 (C6), 12761–12782.

Stansfield, K., Garrett, C., 1997. Implications of the salt and heat budgets of the Gulf of Thailand. Journal of Marine Research 55, 935–963.

Sternberg, R.W., 1968. Friction factors in tidal channels with differing bed roughness. Marine Geology 6, 243–260.

Stewart, R.H., 2006. Introduction to Physical Oceanography. Texas A & M University, p. 344, 〈http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html〉.

Tanabe, S., Nishimura, A., Hanaoka, S., Yanagi, T., Takeoka, H., Tatsukawa, R., 1991. Persistent organochlorines in coastal fronts. Marine Pollution Bulletin 22 (7), 344–351.

Yanagi, T., Sachoemar, S.I., Takao, T., Fujiwara, S., 2001. Seasonal variation of stratification in the Gulf of Thailand. Journal of Oceanography 57, 461–470.

Yelland, M., Taylor, P.K., 1996. Wind stress measurements from the open ocean. American Meteorological Society 26, 541–558.