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The modification of water column conditions in the Gulf of Thailand by the influences of the South China Sea and monsoonal winds

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ABSTRACT

Water column conditions in the Gulf of Thailand (GoT) were analyzed by considering four major factors including surface heat fluxes, freshwater inputs from river discharge and atmospheric fluxes, tidal and wind stirrings. The analytical results suggested that surface heat fluxes and tidal stirring are the most important factors to control water column conditions, followed by freshwater fluxes. Well-mixing was predicted to occur from November to February resulted from relatively large tidal stirring, surface heat loss and low freshwater input, but the climatological density data suggested stratification during this period because of local freshwater accumulation. The South China Sea (SCS) and the northeast wind played significant contributions to freshwater accumulation by generating surface water flow into the gulf during the northeast monsoon. On the other hand, the development of stable and strong stratification during the southwest monsoon was enhanced by SCS subsurface water intrusion and surface outflow induced by the southwest wind. Strong surface heat fluxes coincident with SCS intrusion in April and May make water stratification more complex. This phenomenon generates double thermocline and multi-stratified water in some GoT area.

1. Introduction

Water column conditions in terms of vertical mixing and stratification are important to marine ecosystems and environments. In coastal seas, generally vertical well mixing is dominant due to tidal mixing and wind stirring. Some areas, however, where heat fluxes and freshwater fluxes from river discharge or atmospheric exchanges are very large, water column stratification is able to occur (Buranapratheprat et al., 2008). The conditions of water column are crucial to physical and biochemical environments such as vertical material exchanges and primary productivity of phytoplankton. Water stratification plays as a barrier to nutrient mixing between surface and subsurface waters, resulting in limited nutrient availability and low primary productivity. In contrast, the stratification in a high eutrophic area can generate hypoxia in near bottom water due to organic material decomposition (Zhang et al., 2010). This occurs because dissolved oxygen (DO) is continually consumed while subsurface water is unable to exchange gases with air. Severity of the problem depends on amount of organic material, strength and duration of water column stratification.

The Gulf of Thailand (GoT) locates from latitude 6–14 °N and longitude 99–105 °E (Fig. 1). The area is surrounded by land except in the southeastern part that opens to the South China Sea (SCS). The GoT boundary is straight from the Thai-Malay border to the Cape of Ca Mau in Vietnam with the approximate length of 380 km. The average depth of GoT is about 40 m while the maximum depth is about 80 m located in the center of the area. There is a water sill of depth about 40 m across the GoT mouth. This area is influenced by the Asian-Australian monsoon system-the dry northeast (November-January) and the wet southwest monsoon (May-August). Although there are 11 streams and rivers directly discharging water into the gulf, just four largest rivers namely the Chaophraya, the Maeklong, the Bangpakong and the Tapi are accounted for over 80% of the total input (Snidvongs, 1998). Total discharge emptied into GoT area was estimated to be 129.5 $km^3\ yr^{-1}$ (Stansfield and Garrett, 1997) with largest peak in September or October (Robinson, 1974).

Some works have been done to investigate the controlling mechanism of water column conditions in GoT. Buranapratheprat

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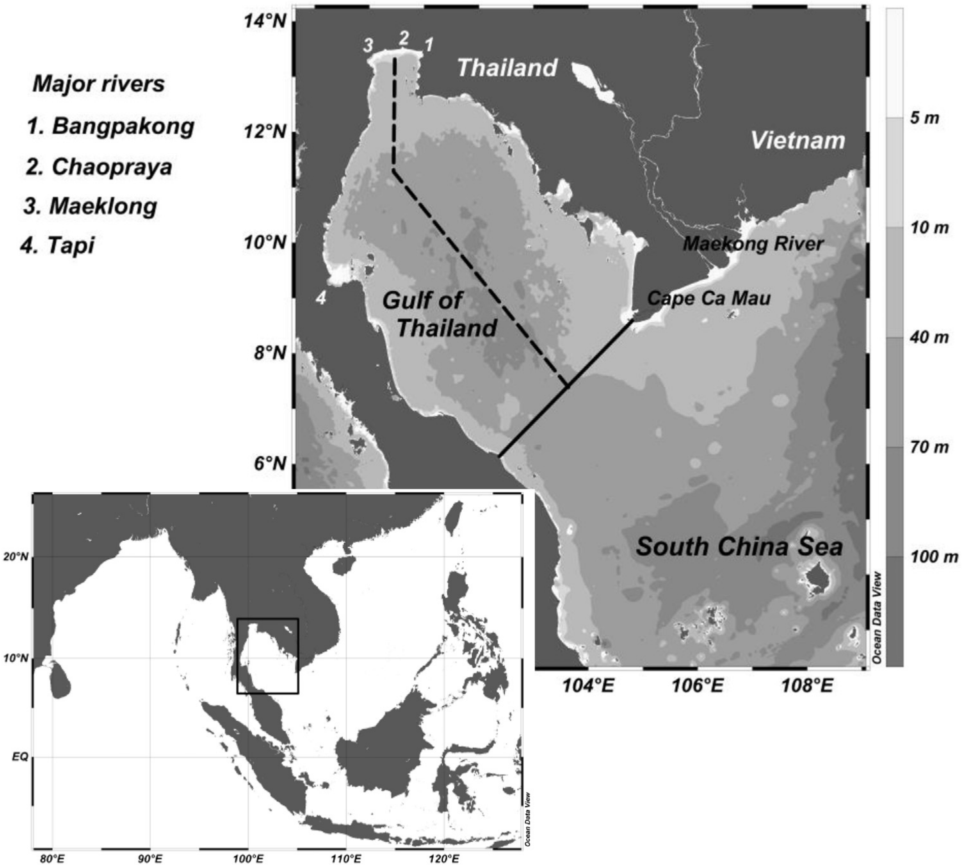


Fig. 1. The Gulf of Thailand showing depth contours in meter and boundary of the study area for water column analysis (thick solid line). The thick broken line is the main axis for cross section plots. Numbers indicate the locations of major river mouths - the Bangpakong (1), the Chaophraya (2), the Maeklong (3) and the Tapi (4).

et al. (2008) has found that both river discharge and surface heat fluxes play as key controlling factors to water column variation in the upper GoT (UGoT). Although the area is very shallow (average depth of 20 m), water stratification is dominant almost year round. Strongest stratification developed in September and October due to large river discharge and moderate heat flux while vertical well-mixing occurred in December due to heat loss, low river discharge and strong wind. The situation is different when the entire GoT is considered by Yanagi et al. (2001). In this case, the influence of freshwater buoyancy flux on water stratification was analyzed to be small compared to surface heat flux. The stratification was therefore strongest during summer, from March to May, following the largest surface heat gain. The influence of the South China Sea (SCS) is also large during this time due to GoT low water density and Ekman transport generated by the southwest monsoon.

Our study will reanalyze water column condition in the whole GoT but this time using different dataset, some derived from satellite remote sensing, and also include air-sea water exchanges. Monthly analysis will be presented and the analytical technique is also modified by taking an account of spatial variation, based on gridded data. This approach is different from the study of Yanagi et al. (2001) who applied just a single box model for the entire GoT area. The influence of SCS on GoT water column and oceanographic conditions will be focused and discussed.

2. Methods

Water column conditions, if stratified or well mixed, are investigated by considering the mean rate of change of potential energy of water column (dV/dt) (Eq. 1). Simpson and Bowers (1981) introduced four significant environmental factors including surface heating, freshwater inputs, tidal and wind stirrings. In this study, however, the buoyancy from atmospheric exchanges (Precipitation (P) and Evaporation (E)) is treated as a significant freshwater source in the analysis. The governing equation is shown as the follow.

$$\frac{dV}{dt} = -\frac{\alpha\, gQH}{2C_p} - \frac{\beta gSH\,(R+P-E)}{2A} + \frac{4\varepsilon\; k_b\rho_w U_t^3}{3\pi} + \delta\; k_s\rho_a W^3 \tag{1}$$

The first two terms on the right hand side represent the influences of buoyancy forces including surface heating, freshwater inputs from river discharge and atmospheric water exchanges, respectively. The third and the forth terms denote the effects of tidal and wind stirrings, respectively. Positive and negative signs are correspondingly assigned to the terms that increase and decrease vertical water column mixing. All constants and variables together with their definitions, values and units are summarized in Table 1.

Surface drag coefficient is treated as a variable due to its sensitivity to wind magnitude (Stewart, 2006). The coefficients, developed by Yelland and Taylor (1996) based on the relationship between wind magnitude at 10 m above sea surface (W_{10}) and surface drag coefficient (C_D), are presented as the follows.

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

$$1000C_D = 0.60 + 0.071W_{10}, \qquad (6 \le W_{10} \le 26\ m\ s^{-1}) \tag{2b}$$

Temperature and salinity data are from NODC World Ocean Atlas 2001 (WOA 2001). They are used to calculate water density

Table 1
Parameters used for the calculation of the rate of change of potential energy in water column.

Symbols	Definitions	Values	Units
α	Thermal expansion coefficient[a]	2.3×10^{-4}	$^{\circ}C^{-1}$
$\boldsymbol{g}$	Gravitational acceleration	9.8	$m\ s^{-2}$
$\boldsymbol{H}$	Water depth (ETOPO5)		m
$\boldsymbol{Q}$	Heat flux		$W\ m^{-2}$
$\boldsymbol{C_p}$	Specific heat of water	0.95	$Cal\ g^{-1}\ {}^{\circ}C^{-1}$
β	Salinity contraction to density[a]	0.001	$g\ cm^{-3}\ psu^{-1}$
$\boldsymbol{S}$	Salinity (WOA2001)		psu
$\boldsymbol{R}$	River discharge		$m^3\ s^{-1}$
$\boldsymbol{P}$	Precipitation		$m^3\ s^{-1}$
$\boldsymbol{E}$	Evaporation		$m^3\ s^{-1}$
$\boldsymbol{A}$	Surface area under river discharge influence		m^2
ε	The efficiency of conversion from turbulence to potential energy for tidal stirring[b]	0.015	
$\boldsymbol{k_b}$	Bottom drag coefficient[c]	2.5×10^{-3}	
$\boldsymbol{\rho_w}$	The density of seawater (WOA2001)		$g\ cm^{-3}$
$\boldsymbol{U_t}$	Tidal magnitude		$m\ s^{-1}$
δ	The efficiency of conversion from turbulence to potential energy for wind stirring[c]	0.039	
$\boldsymbol{C_D}$	Surface drag coefficient (Eq. (2))		
$\boldsymbol{k_s}$	$C_D \times \gamma$		
γ	The ratio of wind-induced current to wind speed[b]	0.0127	
$\boldsymbol{\rho_a}$	The density of air	1.25×10^{-3}	$g\ cm^{-3}$

[a] Yanagi and Takahashi (1988).
[b] Yanagi et al. (2001).
[c] Simpson and Bowers (1981).

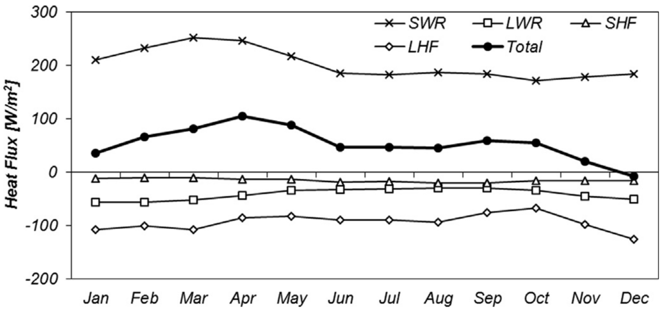


Fig. 2. Averaged monthly surface heat fluxes over the Gulf of Thailand, positive and negative values indicate gaining and loosing heats from the sea surface, respectively. (Source: http://dtsv.scc.u-tokai.ac.jp/j-ofuro/).

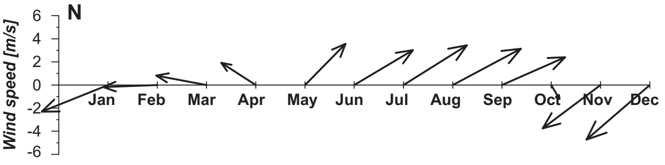


Fig. 3. Averaged monthly wind vectors over the Gulf of Thailand. (Source: http://www.remss.com/).

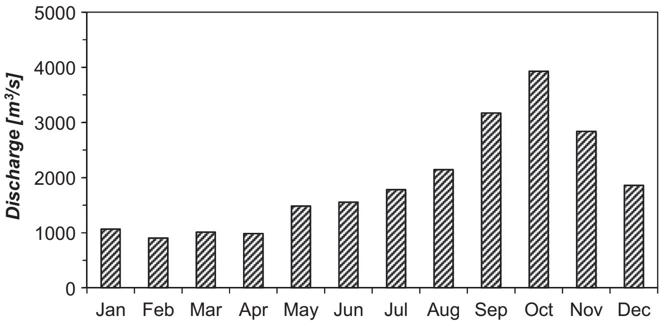


Fig. 4. Average monthly river discharges into the Gulf of Thailand. (Source: the Royal Irrigation Department of Thailand).

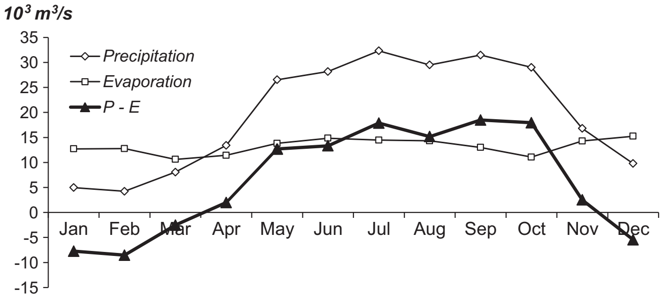


Fig. 5. Average monthly atmospheric freshwater fluxes over the Gulf of Thailand. (Source: http://oaflux.whoi.edu/).

in terms of Sigma-t. Air-sea heat exchanges consider 4 terms including short wave radiation (SWR), long wave radiation (LWR), sensible heat flux (SHF) and latent heat flux (LHF). The data are provided by the School of Marine Science and Technology, Tokai University, available through http://dtsv.scc.u-tokai.ac.jp/j-ofuro/. They have previously been used to analyze annual surface heat fluxes in GoT by Luadnakrob and Buranapratheprat (2012). Monthly wind data from QuickScat (http://www.remss.com/) are used to calculate wind stirring. Annual cycles of average monthly heat fluxes and wind over the gulf area are presented in Figs. 2 and 3, respectively. Monthly river discharge data (Fig. 4) are from Royal Irrigation Department, Thailand. The discharge data were estimated from analytical rating curve based on the relationship between stream level and stream flow. Annual discharge of available data for all major rivers surrounding GoT is about 57 km^3. This value, however, is a half smaller than total discharge and runoff estimated based on all related discharge basin by Stansfield and Garrett (1997) (129.5 km^3). The discharge data of our study are therefore doubled in the analysis (114 km^3). Since the nature of discharge data are lateral characteristic, they are weightily distributed over the surface area. This is based on criteria that low surface salinity area should receive larger discharge than high surface salinity area, and vertical extension of freshwater in each area is proportional to the amount of freshwater the area received. Precipitation and evaporation gridded data over GoT, provided by Woods Hole Oceanographic Institution available at http://oaflux.whoi.edu, are used to calculate net atmospheric freshwater flux (P–E). Average net atmospheric water exchanges for each month are shown in Fig. 5. Tidal data as the combined tidal current amplitudes of K_1 and M_2 (Fig. 6), the most dominant tidal constituents in GoT, are from the results of a numerical simulation by Yanagi and Takao (1998a).

This study treats GoT area as a whole domain containing many small grids inside. The data resolutions of temperature and salinity and wind are $0.25^{\circ} \times 0.25^{\circ}$ surface heat fluxes and atmospheric freshwater fluxes are $1^{\circ} \times 1^{\circ}$ and tidal amplitudes are $2.775^{\circ} \times 2.775^{\circ}$. All data set are equally gridded using Gauss's function to cover the entire study area. The grid positions of temperature and salinity ($0.25^{\circ} \times 0.25^{\circ}$) are used as the reference for interpolation processing. Vertical resolutions of temperature and salinity data in shallow layers are at depths of 10, 20, 30, 50 and 75 m. Weigh-averaging based on depth layers the data belong to is applied to get averaged temperature and salinity over the water column. Long time average data are used for the analysis in order to investigate general monthly water column conditions. All data set except heat fluxes are averaged for 10 years starting from 2000 to 2009. For heat fluxes, data from different periods (1992-

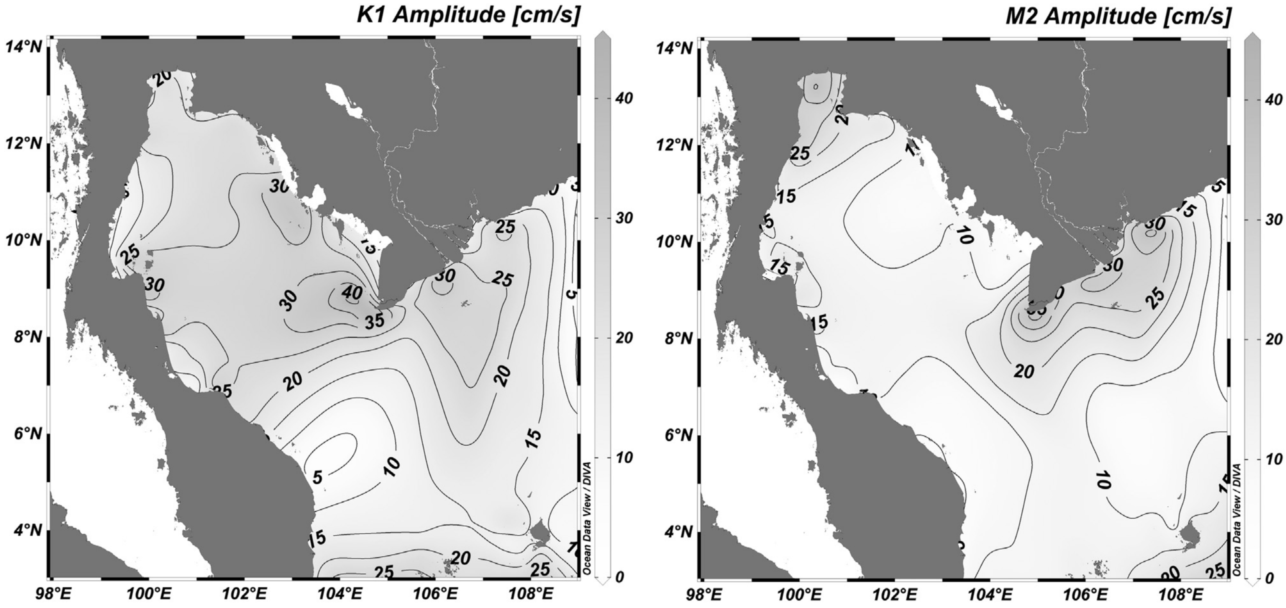


Fig. 6. Tidal current amplitudes of K_1 and M_2 tidal constituents in the Gulf of Thailand. (Source: Yanagi and Takao, 1998a).

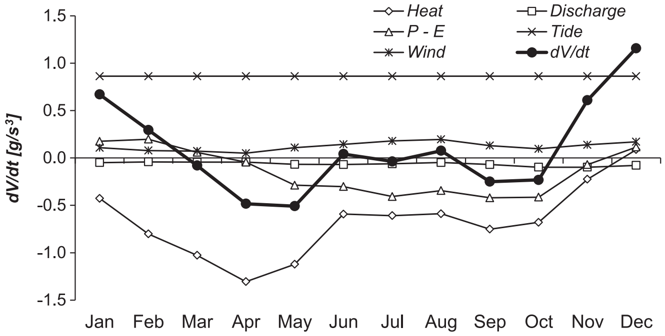


Fig. 7. Monthly variations in the rate of change of potential energy (*dV/dt*) in the water column in the Gulf of Thailand.

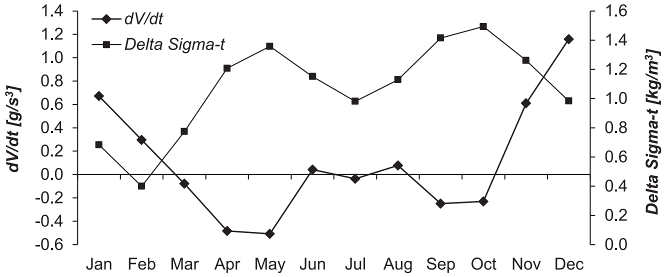


Fig. 8. Monthly variations in bottom-surface density difference (Delta Sigma-t) and the rate of change of potential energy (*dV/dt*) in the water column in the Gulf of Thailand.

2001 for SWR, 1990-1999 for LWR, 1991-1995 for SHF, and 1992-2000 for LHF) are averaged and used in the analysis because of data availability.

SEAFDEC CTD (Conductivity, Temperature and Depth) profile data are also used for the investigation of the influence of SCS on water column conditions in GoT. The data were obtained from intensive hydrographic observations from 5 to 28 September 1995 and from 24 April to 17 May 1996 by MV SEAFDEC at 81 stations in the western GoT and the east of Malaysia Peninsular (Yanagi et al., 2001). The first and second cruises were during the southwest-to-northeast and the northeast-to-southwest inter-monsoon periods, respectively. Ocean Data View (Schlitzer, 2007) is used for contour plots and Microsoft Excel is for graph plots.

3. Results and discussions

3.1. Water column analysis

The potential energy of water column, calculated following Eq. 1, is applied to every grid over the GoT domain. The results of overall spatial averages for individual term on the right hand side and total *dV/dt* of Eq. 1 are presented in Fig. 7. It should be noted that the values of *dV/dt* in positive and negative signs means mixed and stratified water column, respectively. The results of the analysis show that the most significant factors to control water column conditions in this area are surface heat flux and tidal stirring, followed by atmospheric freshwater fluxes, wind stirring and river discharge, respectively.

Heat fluxes in GoT are controlled by SWR and the largest peak of sea surface heating occurs in summer (April–May) (Fig. 2), the period when the sun angle is smallest over Thailand (Luadnakrob and Buranapratheprat, 2012). A minor peak occurs in September and October also during the sun crossing over Thailand's sky but heat flux is not so large because of cloudy and rainy season. The influence of heat energy on water stratification is very small from November to January which is the period of wintertime.

Compared by sources, freshwater buoyancy from atmospheric fluxes (198.92 km^3) to water stratification is greater than from river discharge (114 $km^3\ yr^{-1}$). This is due to larger sea surface area of GoT than the catchment area of rivers surrounding GoT. The small influence of freshwater fluxes may be due to relatively large GoT volume (12,510 km^3) (Stansfield and Garrett, 1997) compared to estimated freshwater entering GoT (312.92 $km^3\ yr^{-1}$) in the analysis. The estimation of the influence of river discharge on water column conditions may not be simple due to many factors such as the distribution of discharged water over the areas and oceanographic conditions. The influence of atmospheric freshwater fluxes varies following monsoonal seasons that large input flux starts in May and ends in October. Sea surface loses water through evaporation from December to March (Fig. 5).

The influence of tidal stirring on water mixing in GoT may be considered by using a tide-induced mixing parameter (Simpson and Hunter, 1974), defined as $\chi = \frac{H}{U_t^3}$, where *H* is the water depth

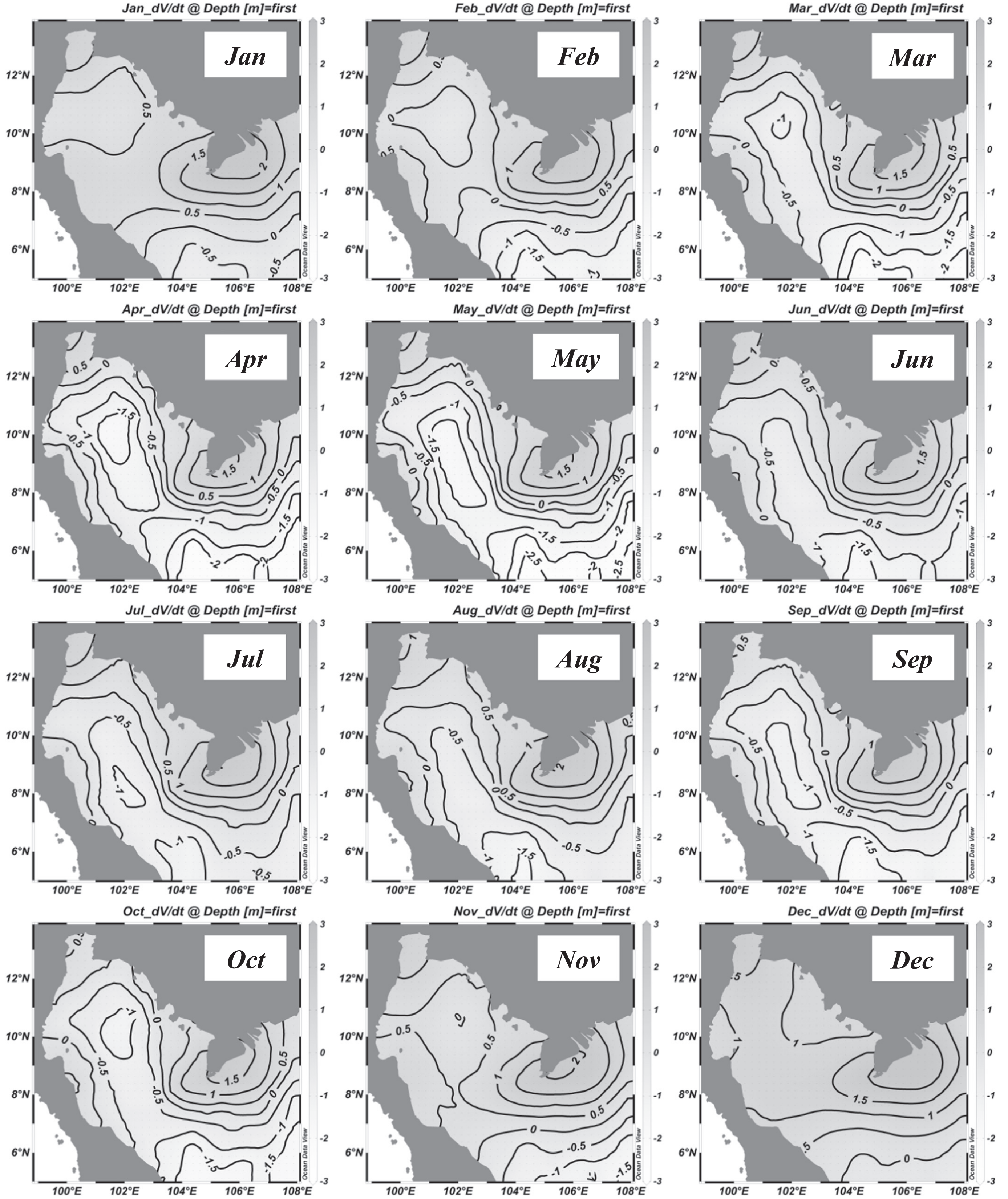
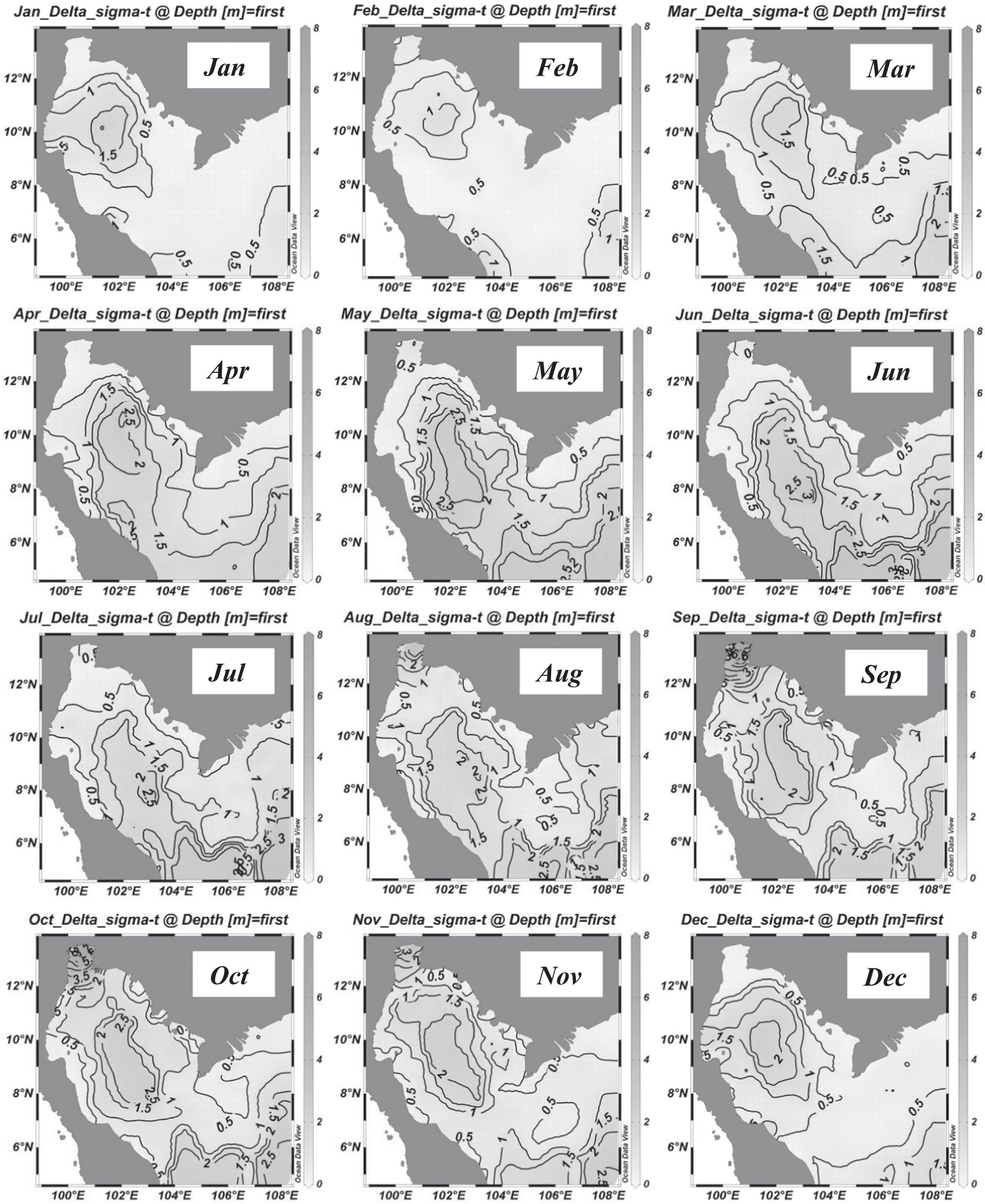


Fig. 9. Horizontal distributions of potential energy (dV/dt) in the water column (g s^{-3}) for every month.

(m) and U_t is the averaged tidal current speed (m s^{-1}). The critical value of χ for vertical mixing in mid-latitudes is about 100 s^3 m^{-2} (Stansfield and Garrett, 1997). M$_2$ and K$_1$ tidal amplitude in the gulf is ranged around 0.5 – 0.8 m s^{-1} (Yanagi and Takao, 1998a). Substituting χ=100 s^3 m^{-2} and U_t=0.5 and 0.8 m s^{-1} in the equation of tide-induced mixing parameter yields H=12.5 m and 51.2 m, respectively. Since the maximum and the average depths of GoT are about 80 m and 40 m, respectively, the critical values



Jan_Delta_sigma-t @ Depth [m]=first

Feb_Delta_sigma-t @ Depth [m]=first

Mar_Delta_sigma-t @ Depth [m]=first

Apr_Delta_sigma-t @ Depth [m]=first

May_Delta_sigma-t @ Depth [m]=first

Jun_Delta_sigma-t @ Depth [m]=first

Jul_Delta_sigma-t @ Depth [m]=first

Aug_Delta_sigma-t @ Depth [m]=first

Sep_Delta_sigma-t @ Depth [m]=first

Oct_Delta_sigma-t @ Depth [m]=first

Nov_Delta_sigma-t @ Depth [m]=first

Dec_Delta_sigma-t @ Depth [m]=first

Fig. 10. Horizontal distributions of bottom-surface density difference (Delta Sigma-t) (kg m^{-3}) for every month.

suggest that tide can induce water mixing in shallow area, leaving stratification in offshore area near the central gulf. Since seasonal variations in tidal current amplitudes in this area have never been reported, they are assumed to be small and treated to be stable throughout the year.

The influence of wind stirring is not so large because wind speed

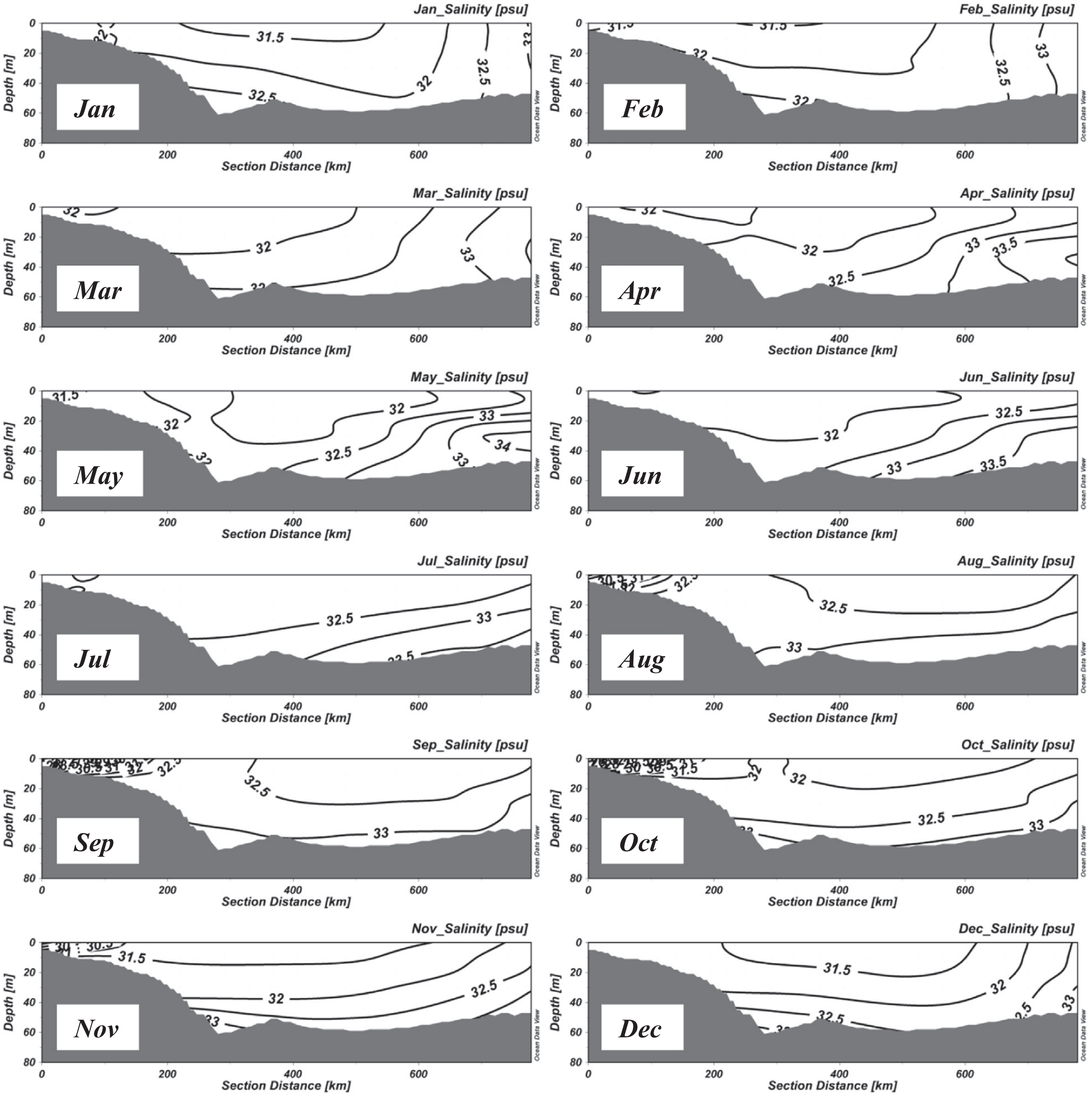
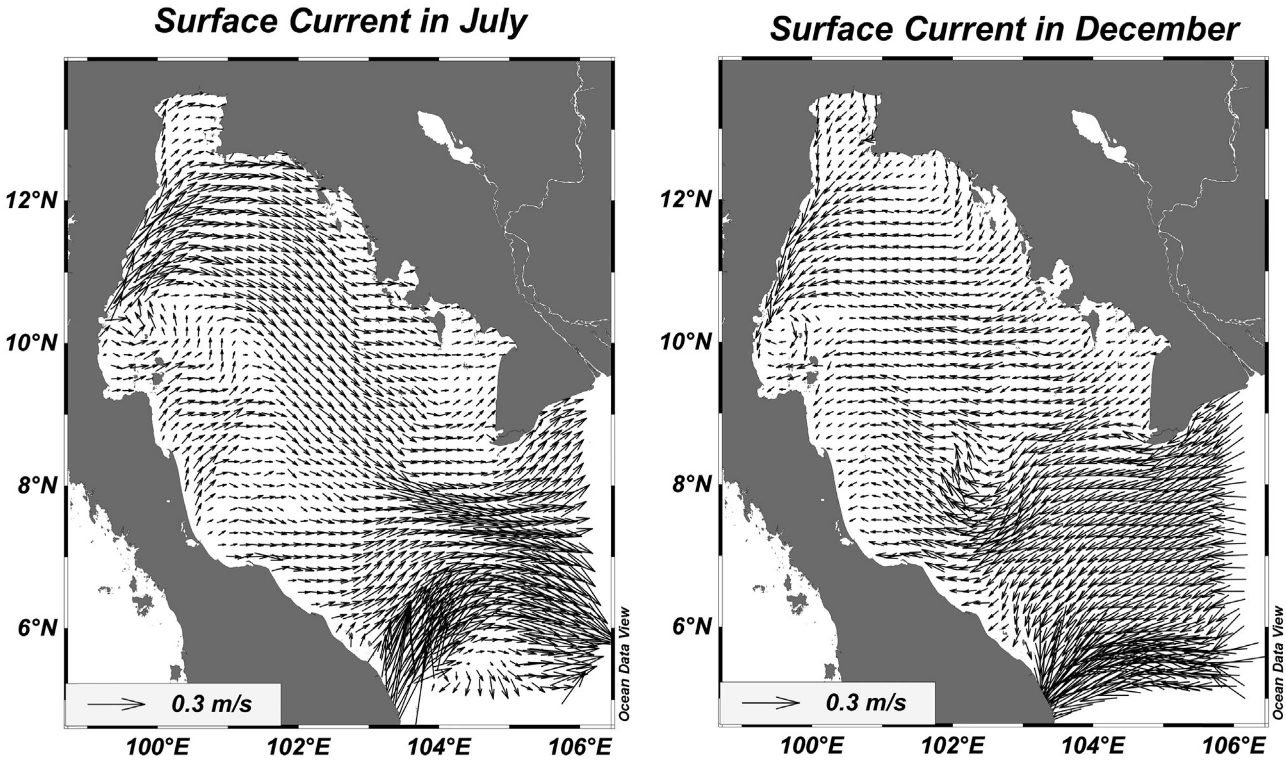


Fig. 11. Vertical distributions of climatological salinity along the main axis in the Gulf of Thailand (Fig. 1) for every month.

over the gulf is not so strong, ranged from 4 m s^{-1} to 9 m s^{-1}. Seasonal variations of wind influence, however, can be observed from Fig. 3 that the potential energy of mixing is high during the northeast or the southwest monsoon and low during the inter-monsoon periods. Compared with tide, wind influence is small, and it cannot generate well-mixing in GoT water column (Fig. 7).

Total *dV/dt* calculated using Eq. 1 reveals that the major peak of estimated stratification occurs in April and May while a minor one occurs in September and October. Surface heat fluxes are the most significant factors to control the variation of water stratifications followed by atmospheric freshwater fluxes. Well-mixing is expected to occur from November to February, observed by negative *dV/dt*, resulted from relatively large tidal stirring, surface heat loss and low freshwater input. Neutral value ($dV/dt \sim 0$) is predicted to occur from June to August when all controlling factors are balanced. It should be noted that variations in sea surface height over the area and planetary wave propagation were not included in the water column analysis because they are unknown for this area and supposed to be small compared to other key factors.

Temporal variation of averaged values over the whole gulf area of *dV/dt* and bottom-surface density difference (delta Sigma-t) is shown in Fig. 8 for comparison between the predicted and the real water column conditions. Generally changes in both values are related to each other that high *dV/dt* occurs when delta Sigma-t is low and vice versa. Negative *dV/dt* and high delta Sigma-t, and positive *dV/dt* and low delta Sigma-t correspondingly occurs from April to October and from December to February, respectively. Some discrepancies are found when they are considered in more details. Highest peak of *dV/dt* (1.16 g s^{-3}) occurs in December but lowest peak of delta Sigma-t (0.4 kg m^{-3}), appears in February, two months after the estimated mixing peak. Disagreement between both values also occurs in summer period. Estimated stratification during June and August dramatically decreases from April and May while delta Sigma-t is still high during the same period. This evidence becomes clear when compared to the situation in March that *dV/dt* value is almost zero, the same as that


Surface Current in July

Surface Current in December

Fig. 12. Monthly surface circulation based on POM during the northeast (December) and the southwest (July) monsoons (Source: Buranapratheprat et al., in preparation).

during June and August, but delta Sigma-t values are much different, 0.77 kg m^{-3} in March and 1.0–1.2 kg m^{-3} during June and August.

Spatial distributions of *dV/dt* (Fig. 9) and delta Sigma-t (Fig. 10) are used to investigate more details of the difference between the predicted and the real water column conditions. Water mixing or low delta Sigma-t appears in shallow water surrounding GoT especially in the area near Cape Ca Mau. This is due to strong tidal stirring because tidal amplitude in this area is quite large (0.6–0.8 m s^{-1}). The predicted values (Fig. 9) show that water mixing in the whole gulf should occur from November to February with the highest peak in December. When compared to delta Sigma-t (Fig. 10), some stratification clearly remains during this period and the mixing shifts to February as mentioned previously. Most stratified waters occur in the middle of GoT and in the southern area outside GoT where water depths are relatively large. They connect to each other during April and August. Only one area of the stratification in the central GoT is left during December and February.

The prediction results suggest well mixing but the real water condition is stratified in the middle gulf from November to February. Cross sectional salinity contours along central axis in Fig. 1 for each month (Fig. 11) are used to investigate both water column conditions and interaction between GoT and SCS water. The conditions of water mass in the south near east Malaysia, however, seem to follow the *dV/dt* prediction that well mixing occurs in winter (Figs. 10 and 11). Stratification in the central gulf in December comes from low salinity water floating over high salinity water. Freshwater may come from local sources surrounding GoT area or from Maekong River as suggested by Stansfield and Garrett (1997). Remaining large volume of freshwater in the gulf during wintertime becomes an interesting issue because local river discharge and precipitation from the dataset are both small (Figs. 4 and 5). This phenomenon may be controlled by oceanographic condition during that time. Since the potential energy of mixing estimated using Eq. (1) considered just instantaneous discharge and precipitation, it becomes unable to reproduce stratification due to freshwater buoyancy in such a case.

3.2. The influences of SCS and monsoonal winds on GoT water column

Why large freshwater still remain in the central gulf during wintertime is first discussed here. Normally precipitation over the area is high from the southwest monsoon to early winter or from May to October while local river discharge has its peak in the inter-monsoon periods or September and October. Accumulation in great amount of freshwater in wintertime is possible because most major rivers, including the Chaophraya River which is the largest river in Thailand, empty their water into the head (the inner part) of GoT. The river water needs periods of time to travel about 800 km to reach the gulf mouth. We do not exactly know its residence time but this may take several months depended on seasonal oceanographic conditions. Freshwater both from river discharge and precipitation can remain in the gulf for longer period during the northeast monsoon than during the southwest monsoon. This is possibly resulted from the surface Ekman Transport because the northeastern wind is supposed to generate inward surface flow directed from the gulf mouth to the inner gulf. This phenomena can be revealed by wind-driven surface currents simulated using the Princeton Ocean Model (POM) as shown in Fig. 12 (Buranapratheprat et al., in preparation). Not just the local wind but SCS water may play a significant contribution to influx water in this season. This phenomenon can make sea level rise in the gulf during the northeast monsoon (wintertime) (Snidvongs, 1998). The results of our study suggest that the influence of SCS and the northeast wind may have a contribution to phases of freshwater by extending its remaining in the gulf in this season. Cross section contours of salinity along the gulf axis (Fig. 11) clearly reveal these variations.

Stable strong stratification developed from April to October while *dV/dt* values suggesting moderate stratification and neutral condition is possibly resulted from SCS water intrusion into GoT. The intrusion is expected to occur when the temperature of GoT water is warmer than that of SCS in summertime. This density-driven circulation generates surface outward flow in the same

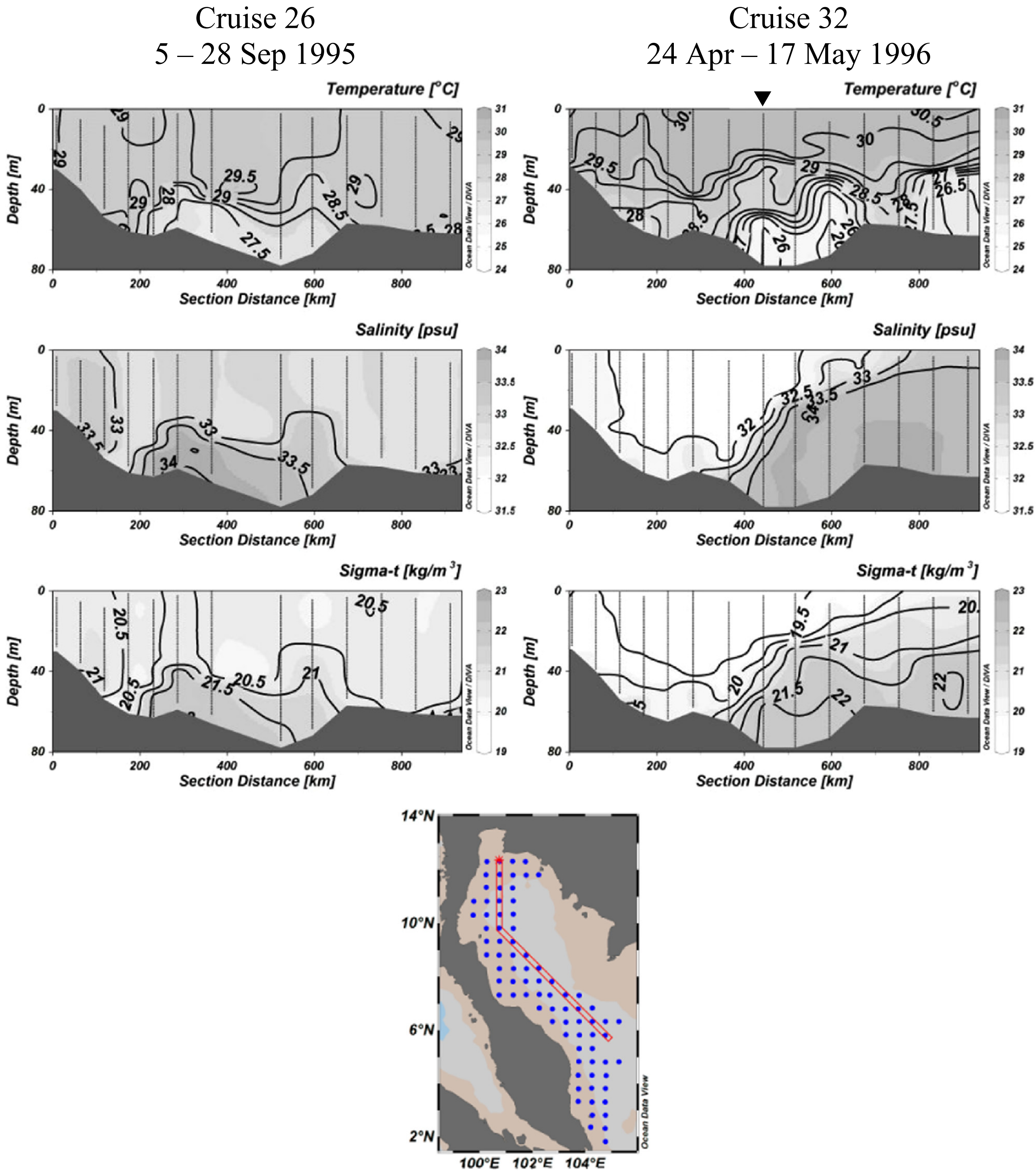


Fig. 13. Vertical distributions of temperature, salinity and Sigma-t along the main axis in the Gulf of Thailand during SEAFDEC cruise 26 (5–8 September 1995) and cruise 32 (24 April - 17 May 1996).

direction to Ekman surface current induced by the southwest wind (Fig. 12). Subsurface water intrusion from SCS becomes more intense and strong stratification in the gulf occurs throughout this season. Cross sections of salinity contours near the gulf mouth (Fig. 11) clearly animate this dynamics that the intrusion of SCS starts in April and ends in November.

The residence time of freshwater should be short in summer (the southwest monsoon) following enhanced density-driven current and long in winter (the northeast monsoon) resulted from inflow water from SCS. To confirm this hypothesis, we will do a numerical passive tracer experiment using POM to investigate seasonal variations in GoT residence time in the near future. The influence of tide-induced residual current on seasonal residence time is assumed to be small compared to wind forcing because the sea surface wind curl plays a very important role in the determination of residual flow pattern in GoT (Yanagi and Takao, 1998b). Besides the volume of freshwater inputs, residence time of freshwater play a crucial role to control salinity in the area. Salinity, therefore, should be higher and lower than normal during the southwest and the northeast monsoon, respectively. This is used to explain unusual low salinity in GoT during winter because of long freshwater residence time besides the influence of other freshwater sources e.g. the Mekong River, as suggested

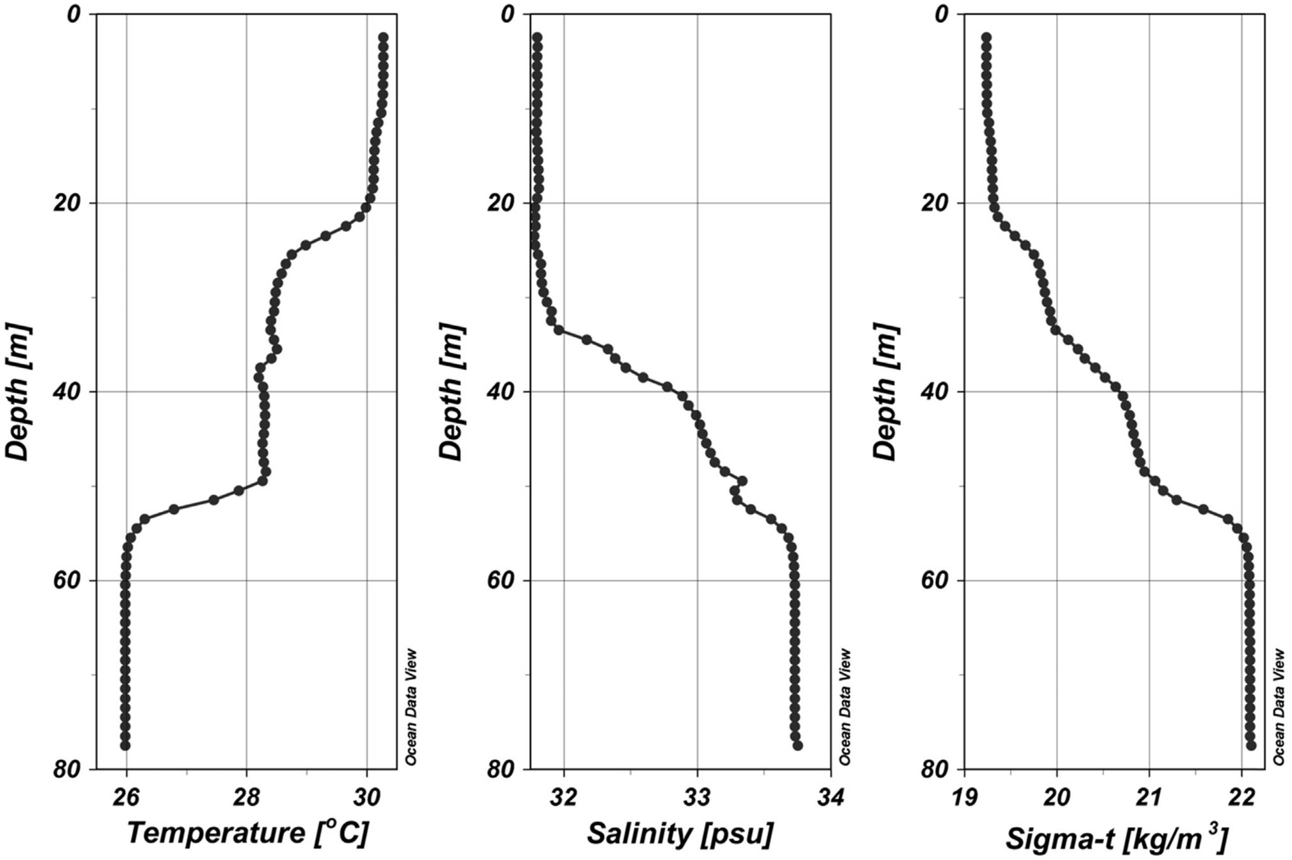


Fig. 14. Temperature, salinity and Sigma-t profiles at a station in the central GoT during SEAFDEC cruise 32 (24 April - 17 May 1996).

in Stansfield and Garrett (1997). Our results suggest that if the residence time of freshwater from local sources is appropriately applied, salt balance in the gulf may be achieved. Our future researches will be focused to this direction.

Although climatological WOA 2001 data provide valuable information on SCS water intrusion into GoT, some oceanographic details may be lost due to gridding process. The data from MV SEAFDEC from 2 cruise surveys in the western GoT and east Malaysia peninsular during 5–28 September 1995 and 24 April–17 May 1996 are used to investigate in more details on related oceanographic phenomena. Vertical cross sections of temperature, salinity and Sigma-t along main GoT axis are presented in Fig. 13. The intrusion from the SCS water can be observed in both periods. Cold and salty water lied down near sea bottom in the central gulf during September while such water mass started to intrude into the gulf during April and May. These changing snapshots agree well to WOA 2001 data presented in Fig. 11, suggesting reliability of this climatology data used in this analysis. Strong surface heat fluxes coincident with SCS intrusion in April and May make water stratification more complex in some area. Both factors support thermocline development but at different water depths. Temperature, salinity and Sigma-t profiles of a station near central GoT (a station with black triangle in Fig. 13) suggest that thermocline generated by surface heat fluxes locate at depth around 20–25 m while that generated by SCS intrusion locate at depth around 50–55 m (Fig. 14). We know that the lower thermocline is generated by SCS water mass because of high salinity coincidence. This double thermocline and halocline make pycnocline or water column condition more complex. This phenomenon may play some key roles on vertical mixing, turbulence, material transport and primary productivity in this area.

4. Conclusion

Water column analysis for GoT suggests that surface heat fluxes and tidal stirring are the most important to control water column conditions, followed by freshwater fluxes. Not only in summer but also in winter, the stratification develops because of local freshwater accumulation in the gulf instead of surface heating. SCS and the northeast wind play a significant contribution to water accumulation by generating water flow into the gulf via the gulf mouth. The development of stable and strong stratification is also related to SCS subsurface water intrusion into the gulf in summer enhanced by outward surface flow out of the gulf. This phenomenon generates double thermocline and multi-stratified water in some GoT area.

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