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Divergence/convergence field observed with GPS tracked drifters in the Upper Gulf of Thailand

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Abstract—The relationship between the divergence/convergence field and chlorophyll *a* concentration in the surface layer of the Upper Gulf of Thailand is investigated by field observations of hydrographic parameters including temperature, salinity, nutrients, chlorophyll, and other properties, and experiments using GPS tracked drifters. The field observations were carried out on board a research vessel *Kasetsart I* and a fishing boat in May and October 2004, and February 2005. It is found that there is a clear correlation in a qualitative sense between divergence field and chlorophyll *a*, in which relatively higher chlorophyll *a* is observed in a divergent condition, with an exception at one station where the opposite relation is indicated possibly because of some local effects of a nearby island upon the surface currents. Such a clear correlation, however, can not be explained by a hypothetical scenario that surface divergence sustains a high chlorophyll *a* by supplying water of high nutrients from the lower layer, having been considered the distribution of nutrients and other hydrographic structures.

Key words: divergence, convergence, surface drifters, Gulf of Thailand, GPS, primary production

Introduction

The Upper Gulf of Thailand (UGOT) is one of the key areas for the coastal zone management in Thailand. It is the northern part of the Gulf of Thailand, having a dimension of approximately 100 km both in latitude and longitude, and the maximum water depth at about 40 m. It has been eutrophicated due to anthropogenic inputs mainly from the metropolitan area of Bangkok. There are four major rivers including Banpakong, Chaopraya, Thachin, and Maeklong from east to west, which supply fresh water together with land-originated materials into the northern part of UGOT (Fig. 1). Several issues including marine pollution, primary production and red tide occurrence have been raised to understand environmental conditions of UGOT. As the relationship between the primary production and water circulation is one of the most important topics among these issues, studies on basic mapping of the productivity (Matsumura et al. 2004) and simple modeling of the circulation of UGOT (Branapratheprat et al. 2002) were carried out.

With regard to the productivity, it shows inhomogeneous distribution in space and seasonal changes based on the maps of ocean color derived from satellite images (Matsumura, personal communication). Considering that the spatial distribution of the productivity is strongly influenced by the circulation field as well as other oceanographic conditions such as temperature, salinity and nutrient distribution, we have carried out a series of observational cruises in UGOT since May 2004 to collect oceanographic data of water circulation and hydrography. Our main motivation of the present study is to understand the relationship between divergence/convergence field in the surface layer and chlorophyll *a* concentration as a possible indicator for primary production. As a background idea of this motivation, we have had a hypothetical scenario to explain the inhomogeneous distribution of chlorophyll *a* before designing the observational plans. If the surface layer of UGOT is under an oligotrophic condition and nutrients are rich in the lower layer, higher chlorophyll *a* should be observed in the area of surface divergence where the water of high nutrient concentration will be upwelled. If it is under highly eutrophic condition, on the other hand, surface convergence may generate the area of relatively high concentration of chlorophyll *a*.

With regard to the circulation field of UGOT, Buranapratheprat et al. (2002) made a numerical model to describe seasonal changes of the currents. They presented a general pattern of the circulation for the whole UGOT. Their model does not have enough spatial resolution to discuss about the relationship between the productivity and current field, nor is not applicable to examine divergence/convergence field.

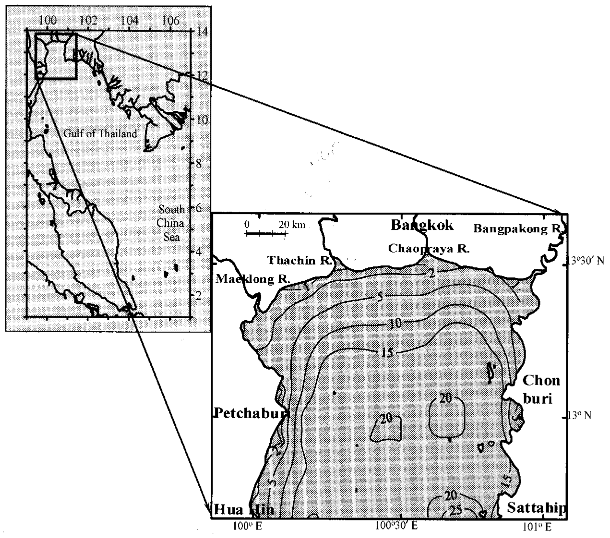


Fig. 1. The Upper Gulf of Thailand, showing its bottom topography with contours of depth in meters.

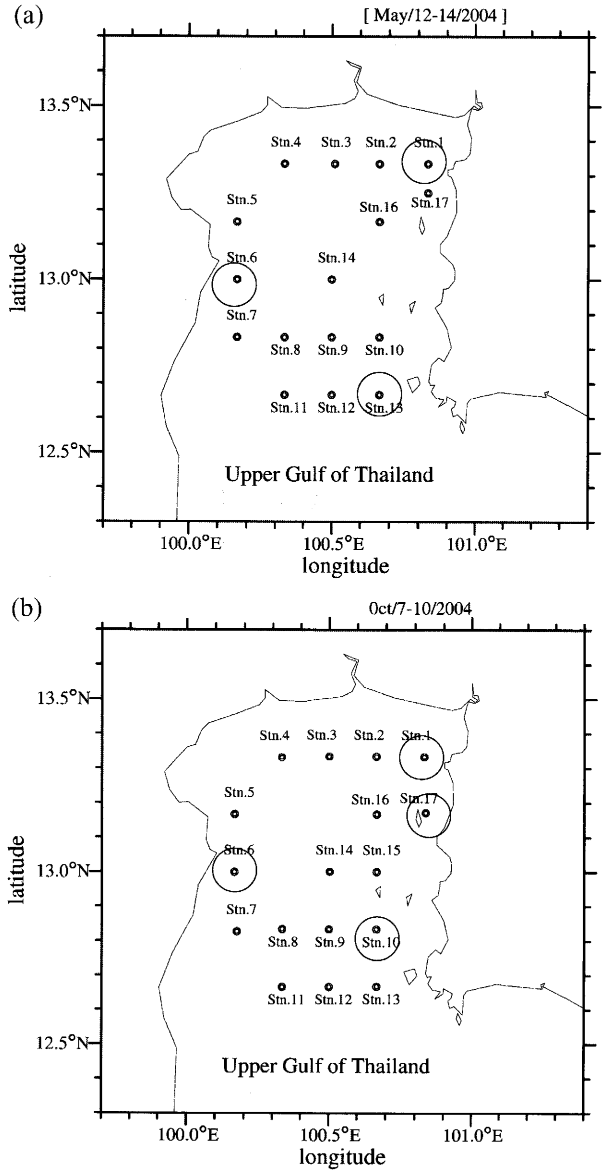


Fig. 2. Location of CTD stations (dots with numbers) and the sites of buoy experiments (larger circles) in the Upper Gulf of Thailand, for (a) the first cruise in May 2004, and (b) the second cruise in October 2004.

In order to directly estimate the divergence/convergence field in UGOT, we made buoy experiments by deploying surface drifters that could be tracked their positions with GPS loggers during the observational cruises we did. We analyze the trajectories of drifters to calculate the divergence term ($\delta u/\delta x + \delta v/\delta y$) and compare them with oceanographic conditions, particularly with the chlorophyll *a* concentration.

Field experiments and observations

Observational cruises on board *R/V Kasetsart I* of the Kasetsart University and a fishing boat were carried out three times, in May 2004, October 2004, and February 2005. CTD casts, water sampling for nutrients and chlorophyll *a* analysis, and buoy experiments to estimate divergence field were made in all the cruises. These observations were implemented only during the daytime. In the first and second cruises, observations of light condition related to photo-synthesis activity were also carried out by other research group on board *R/V Kasetsart I*. CTD and water sampling stations were extended in the entire UGOT for the first and second cruises, where there were 16 and 17 stations, respectively. Stations in the third cruise were located in the north-eastern corner of UGOT, mainly because we were on board a fishing boat without using the research vessel of the Kasetsart University and could not go further inside of the Gulf. Buoy experiments were made 3 to 4 times in each cruise. The outline of three cruises and observed parameters are summarized in Table 1, and station maps are shown in Fig. 2.

A direct-reading type CTD (YSI Model 600XL) was used to collect hydrographic data from the surface to bottom. Parameters measured are temperature, salinity, dissolved oxygen, pH and turbidity. Sea water at surface, 5 m, and 10 m were sampled with a Van Dorn water sampler for nutrients and chlorophyll *a* analysis. Sampled water for nutrients was kept in freezer until analysis in a chemical laboratory of Chulalongkorn University after cruise. Nitrate (NO_3) and phosphate (PO_4) were measured using a spectrophotometer. chlorophyll *a* samples were collected into polyethylene bottles, and 100 ml of them was filtered through a GF/F filter paper with suction. The filter samples were wrapped in foil and stored in freezer until analysis. Pigment trapped on the filter was exacted in a dark polyethylene tube by 90% acetone into 10 ml. Then chlorophyll *a* was measured with a spectrofluorometer that was calibrated with a set of standard solutions prepared in the laboratory of Chulalongkorn University.

Table 1. Summary of three cruises in the Upper Gulf of Thailand from May 2004 to Feb. 2005.

Cruise	Date	Vessel(s)	Observation Parameters	Buoy Exp.	CTD Stations
1	May 12–15, 2004	*Kasetsart I*	CTD, Chlorophyll *a* Light condition, Nutrients	3	16
2	Oct. 7–10, 2004	*Kasetsart I* Fishing boat	CTD, Chlorophyll *a* Light condition, Nutrients	4	17
3	Feb. 5–6, 2005	Fishing boat	CTD, Chlorophyll *a*	4	4

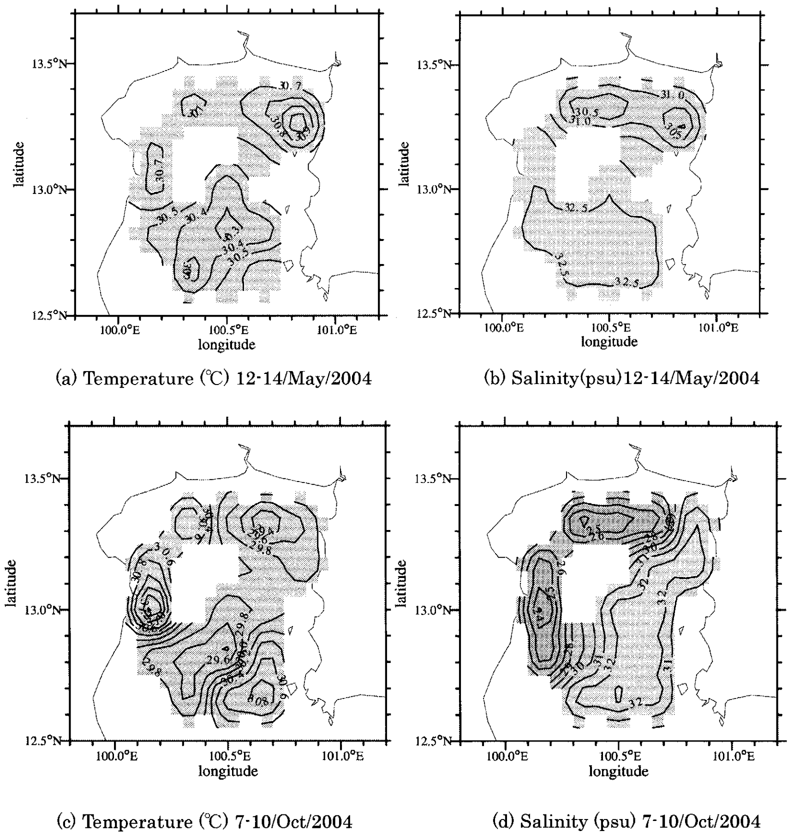


Fig. 3. The distribution of water masses on the sea surface. (a) Temperature in degree-C, and (b) salinity in PSU for the first cruise in May 2004. (c) Temperature, and (d) salinity for the second cruise in October 2004. The areas of no data are left as blank in the central part of the gulf and coastal regions.

GPS tracked drifter used in the experiments is designed according to the specification presented by Michida et al. (2004). A GPS logger is put on the top of a buoy. A cylindrical drogue of 0.6 m in diameter and 1.1 m in length (holey sock type) is connected with a flexible joint to the main part of the drifter to reduce the wind slip effects upon the drifter's motion. The depth of drag center of the drogue is set at about 5 m below the sea surface. The accuracy of the positioning with the GPS logger has been estimated approximately at 5 m (Michida et al. 2004). We set the location interval at 5 minutes throughout the experiments, which means that the accuracy of velocity observed with drifter is less than 2.5 cm/sec.

We deployed 5 to 8 drifters in each experiment to make a polygon cluster (square, pentagon, and hexagon, depending on the experiment) with a few hundred meters side scale of each polygon. After tracking them for 1 to 3 hours, we recovered all of the drifters. Location data recorded on GPS logger were analyzed to estimate divergence/convergence field according to the method described by Aoyagi et al. (2004) and Kawai (1976).

Results

Hydrographic conditions in the experiments

We describe hydrographic conditions in the experiments in this section as background information for divergence and convergence field. Temperature and salinity distributions at the sea surface for the first and second cruises are shown in Fig. 3. The first and second cruises were carried out in May 2004, at the beginning stage of the southwest monsoon season, and in October 2004, at the beginning stage of the northeast monsoon, respectively. In other words, they were both in transition period of monsoons. The third cruise was in February 2005, in the middle stage of the northeastern monsoon. According to the meteorological data collected on board these cruises, relatively constant southwest wind over 5 m/sec was dominant during 4 days in the first cruise. In the second cruise, however, wind condition varied by stations and dates, and the wind speed was less than 5 m/sec throughout the cruise. Sea surface wind was not measured on board a fishing boat in the third cruise.

In the first cruise (Fig. 3a, 3b), coastal water of low salinity accumulated in the northern part of UGOT, while the water of higher salinity originated in the lower Gulf was in the southern region of UGOT. Temperature distribution also showed a contrast between the northern and southern halves, warm in the north and cold in the south. At the same time, however, warm water masses of smaller scale were observed in the western coast and the region of southeast corner. Figures 4a and 4b display vertical structure of temperature and salinity at stations 1, 6, and 13, where buoy experiments were made. Salinity was almost homogeneous vertically at all of these stations. Temperature was also homogeneous vertically at Stn. 6, while at other two stations some stratification was observed.

In the second cruise (Fig. 3c, 3d), coastal water of extremely low salinity less than 25 psu was in the northwestern half of UGOT, and the water of higher salinity covered the rest of the Gulf. Looking at the temperature distribution, warmer water masses were observed at the northwest and southeast corners, while water of low temperature covered the central part of the gulf. There was big difference in salinity between Stn. 1 and 2 in the northeast region of the gulf. We note that a remarkable front was observed at Stn. 2, where a lot of marine debris were found along the front. A water mass of high temperature and low salinity existed in the surface layer above 5 m at Stn. 6 that made strong stratification. Figure 4c and 4d display vertical structure of temperature and salinity at the stations where buoy experiments were made. Stratified structure found in Stn. 6 and 10 seemed to be confined in very surface layer, and to have a pycnocline at shallower than 5 m.

As observations in the third cruise are limited in a smaller region in comparison to the first and second cruise, we see only vertical structure of temperature and salinity ob-

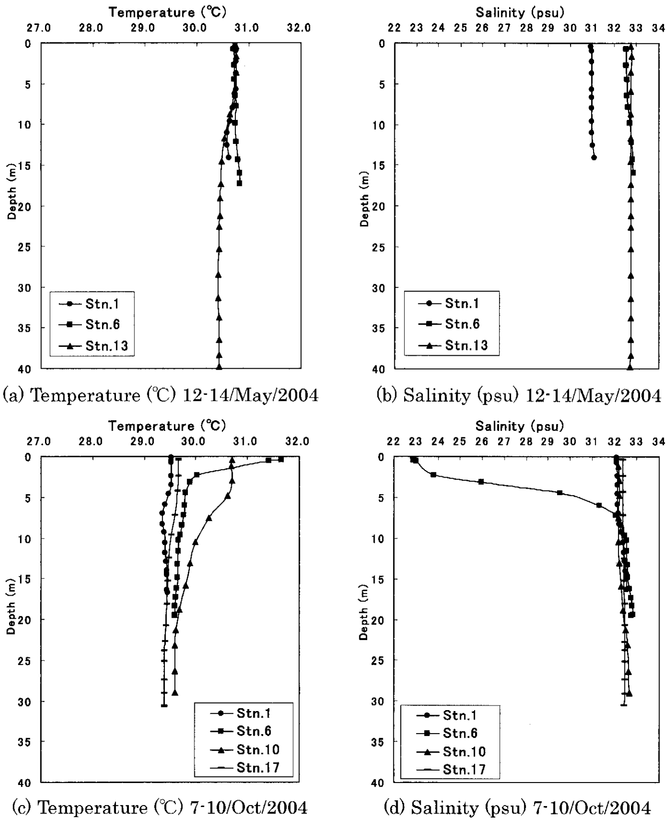
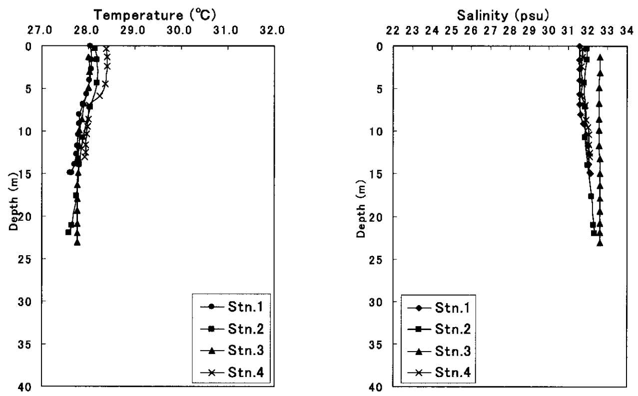
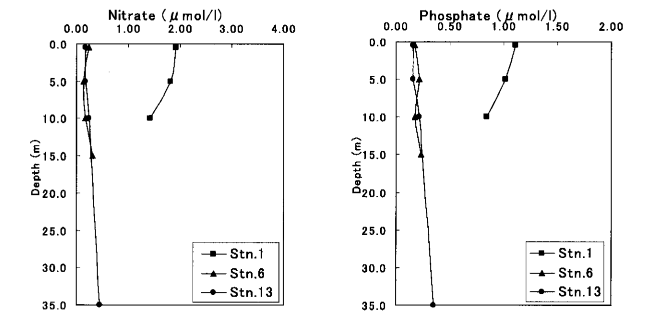


Fig. 4. Vertical profiles of temperature and salinity at stations where buoy experiments were made. (a) Temperature in degree-C, and (b) salinity in PSU at Stations 1,6, and 13 during the first cruise in May 2004. (c) Temperature, and (d) salinity at Stations 1, 6, 10, and 17 during the second cruise in October 2004.

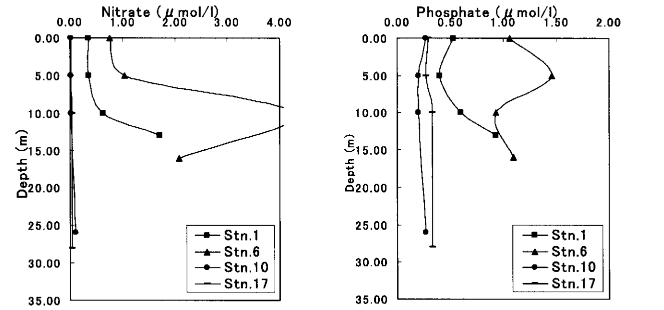


(a) Temperature (℃) 5-6/Feb/2004 (b) Salinity (psu) 5-6/Feb/2004

Fig. 5. Vertical profiles of, (a) temperature in degree-C, and (b) salinity in PSU at stations where buoy experiments were made during the third cruise in February 2005.



(a) Nitrate (μmol/l) 12-14/May/2004 (b) Phosphate (μmol/l) 12-14/May/2004



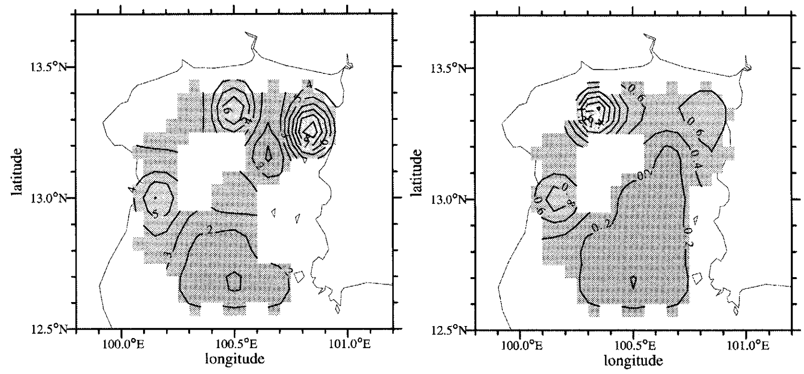
(c) Nitrate (μmol/l) 7-10/Oct/2004 (d) Phosphate (μmol/l) 7-10/Oct/2004

Fig. 6. Vertical profiles of nutrients at stations where buoy experiments were made. (a) nitrate, and (b) phosphate at Stations 1,6, and 13 during the first cruise in May 2004. (c) nitrate, and (d) phosphate at Stations 1, 6, 10, and 17 during the second cruise in October 2004.

served in association with buoy experiments. The vertical profiles of temperature and salinity shown in Fig. 5 indicate that there was not significant stratification during the experiments.

With regard to the vertical distribution of nutrients, Fig. 6 shows its profile of nitrate and phosphate at stations where buoy experiments were made in the first and second cruises. High nutrients in the subsurface were observed at Stn. 1 and 6 in the second cruise (Fig. 6c and Fig. 6d). At other stations in the first and second cruises, the vertical profile of nutrients was rather homogeneous, among which nutrients in the surface layer was slightly higher than those in the subsurface at Stn. 1 in the first cruise.

The distribution of chlorophyll *a* concentration is shown in Fig. 7. We will see it as an available indicator of the productivity, though the concentration of chlorophyll *a* in the surface layer may not directly reflect the primary production of the water column. It was observed from a macroscopic viewpoint that the concentration of chlorophyll *a* was lower in the mouth of UGOT and higher in the northern end. However, there seemed to be big difference by stations for both in the first and second cruises. For example in the first cruise (Fig. 7a), high values were measured at Stn 1, 3, and 6, showing a strong contrast to the neighboring stations where relatively low values were observed. Similarly in the second cruise (Fig. 7b), chlorophyll *a* was relatively high at Stn. 1, 4,



(a) Ch-a (μ g/l) 12-14/May/2004 (b) Ch-a (μ g/l) 7-10/Oct/2004

Fig. 7. The distribution of chlorophyll *a* in μg/l at the sea surface, (a) for the first cruise, and (b) second cruise.

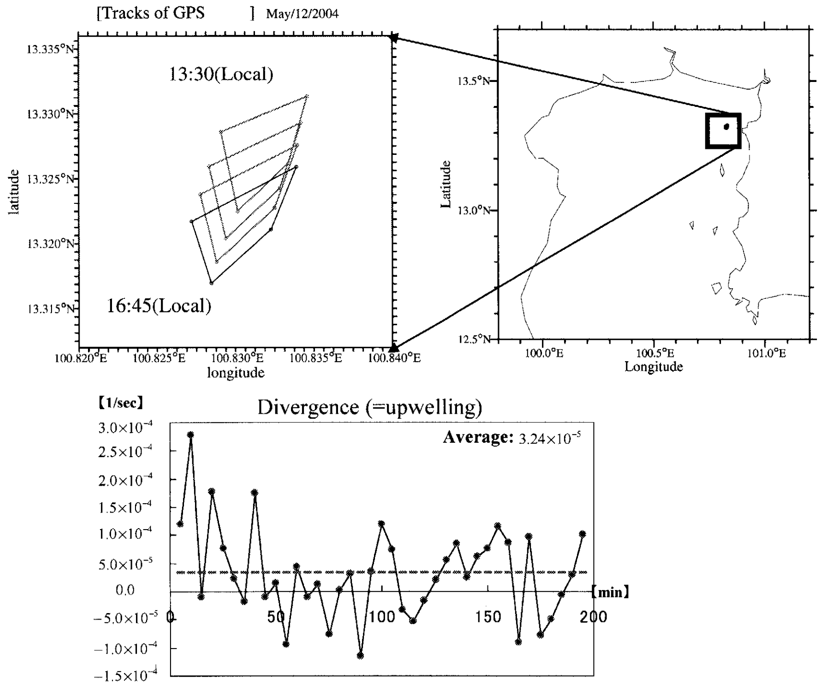


Fig. 8. Result of a buoy experiment on May 12, 2004. (top right) the site of experiment, (top left) movement of the polygon of buoys from the deployment to recovery, and (bottom) the divergence term calculated from buoy motions in every 5 minutes, showing the average value with a dashed line.

and 6, while that was low at other stations.

In the third cruise, experiments and hydrographic observations were carried out around Stn. 1 and amongst station between Stn. 1 and Stn. 16 on the first day of the cruise, on February 5, 2005, and at Stn. 1 and 16 on the second day, February 6, 2005. Both relatively high and low concentration of chlorophyll *a* was observed twice each among these four experiments.

Relation between divergence/convergence field and chlorophyll *a* concentration

Buoy experiments were made to estimate divergence field 3 times in the first cruise, 4 times in the second cruise, and 4 times in the third cruise, respectively. Each trial was carried out under different experimental conditions; location, time, and duration of tracking, and also weather. Figure 8 and 9 show typical two results for divergence and convergence. The experiment presented in Fig. 8 was carried out at Stn. 1 on May 12, 2004 during the first cruise, by deploying drifters to form a square and tracking them for 3 hours. The square cluster of buoys drifted in southwest direction with its averaged speed of less than 5 cm/sec, and showed stretching transformation in east-west direction. Estimated divergence term varied in time. Although sometimes it took even negative values, it was estimated to be a divergent field in average over the period of experiment. The experiment presented in Fig. 9 was carried out at Stn. 17 on October 7, 2005 during the second cruise, by deploying drifters to form a pentagon

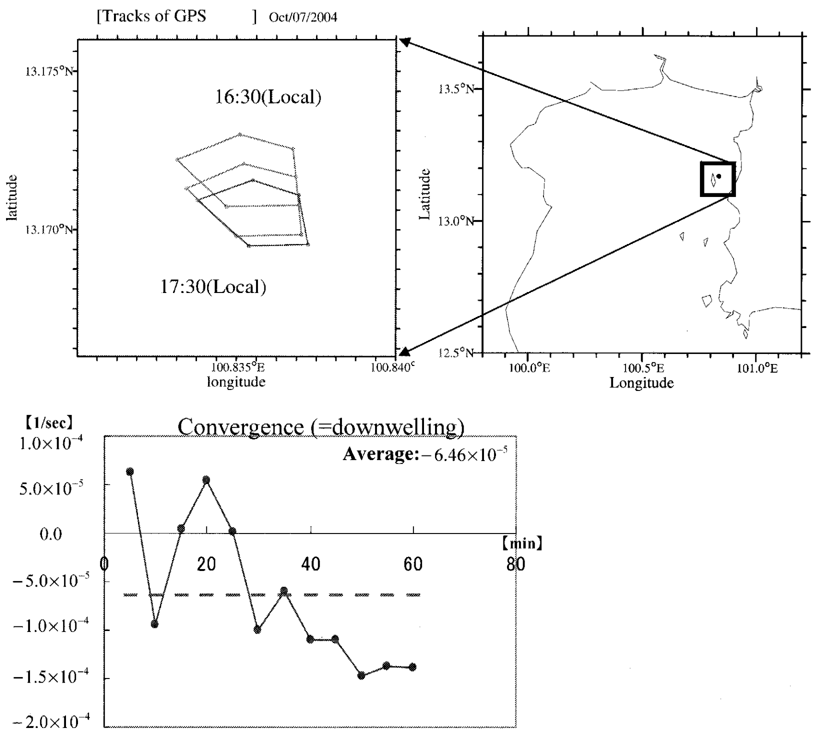


Fig. 9. Same as Fig. 8, except for an experiment on October 7, 2004.

Table 2. Summary of the buoy experiments carried out during the cruises in Table 1 to estimate divergence/convergence field in the Upper Gulf of Thailand.

Cruise	Exp.	Date	Place	Polygon	Hours	Divergence ($\times 10^{-5}$ sec^{-1})	Chlorophyll *a* (μg/l)
1	1	May 12, 2004	Stn. 1	4	3.25	3.2	6.0
	2	May 13, 2004	Stn. 6	4	1.00	2.4	6.4
	3	May 14, 2004	Stn. 13	4	1.00	−4.6	1.1
2	4	Oct. 7, 2004	Stn. 1	5	2.00	1.0	0.83
	5	Oct. 7, 2004	St.n 17	5	1.00	−6.5	0.58
	6	Oct. 8, 2004	Stn. 6	5	1.50	13.4	0.97
	7	Oct. 9, 2004	Stn. 10	4	1.00	−5.6	0.08
3	8	Feb. 5, 2005	Stn. 1	6	2.00	2.8	44
	9	Feb. 5, 2005	Midst of Stn. 1 and 16	6	1.50	−3.4	27
	10	Feb. 6, 2005	Stn. 16	6	1.75	−1.9	9.3
	11	Feb. 6, 2005	Stn. 1	6	1.50	1.8	38

and tracking them for one hour. The pentagon cluster of buoys drifted in southeast direction with its averaged speed of 10 cm/sec, and showed reduction of its area. Estimated divergence term was sometimes positive in the early stage of experiment, and consistently negative in the latter half. Then it was estimated to be a convergent field in average over the period of experiment.

The results of all eleven experiments for three cruises are summarized in Table 2. The surface current field is estimated to be divergent in 6 experiments and convergent in 5 experiments. Comparison of the divergence term and chlorophyll *a* concentration is shown in Fig. 10, using different symbols by cruises. Although the level of chlorophyll *a* concentration varies by cruises: the highest in the third cruise in February 2005, the lowest in the second cruise in October 2004, and medium in the first cruise in May 2004, a clear positive correlation that higher chlorophyll *a* is in divergent conditions can be seen in the relation between the divergence term and chlorophyll *a* concentration in each cruise.

Discussions

A clear correlation is observed between the divergence/convergence field estimated from the movements of drifters and the concentration of chlorophyll *a* for each

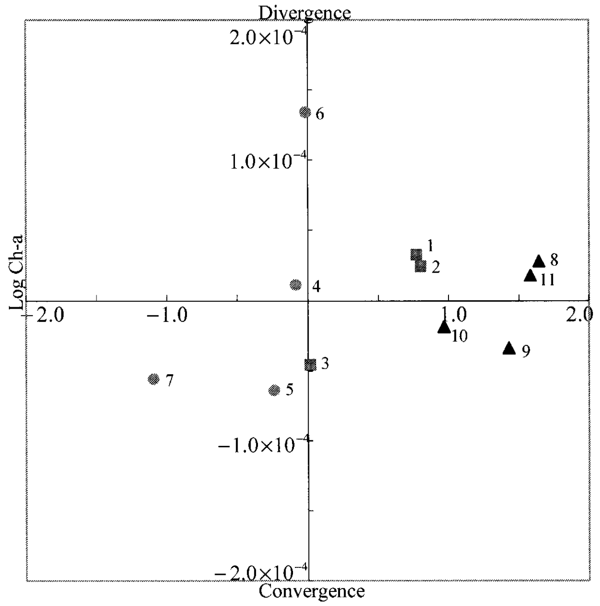


Fig. 10. Comparison of chlorophyll *a* concentration in the surface layer and divergent term calculated from buoy experiments, as listed in Table 2. Squares are for the first, circles for the second, and triangles for the third cruises. Numerals suffixed to the symbols indicate the experiment number.

cruise. It seems to be supportive to one of the hypothetical scenarios in our mind before the experiments. However, it is only applicable in an oligotrophic surface layer, where surface divergence would supply nutrient rich water upwelled from the deeper layer and result in higher chlorophyll *a* there. Vertical distribution of nutrient (Fig. 6) shows a homogeneous structure at many of the stations. And at some stations, nutrients are even richer in the surface layer than in the lower layer. These facts regarding nutrient distribution suggest that nutrient supply from the lower layer would not simply sustain the chlorophyll *a* concentration in the surface layer of UGOT. Based on the observation of light condition, it is reported that there is enough light for photosynthesis even in the bottom layer of UGOT and, it is not a restriction for production (Matsumura, personal communication). Having these discussions, as the reason for the correlation has been still unclear, we need to verify whether the relationship observed in the present study is realistic by examining more cases.

The data point for the experiment 5 in Fig. 10 seems to be somehow out of the correlation between convergence and chlorophyll *a*. It shows approximately 7 times higher chlorophyll *a* than that for experiment 7, though convergent field is estimated for both experiments. The experiment 5 was carried out at Stn. 17 very close to an island (Fig. 2b), where the condition of current field was different from that in other stations. The tidal current influenced by the island may have caused some localized effects on convergent surface currents. This may be one of possible reasons for the discrepancy of experiment 5 in the relationship shown in Fig. 10 and Table 2.

Buoy experiments were carried out four times at Stn. 1, for experiments 1, 4, 8, and 11. Divergent current field was observed in all of these experiments in different seasons. This result suggests a possibility that the surface current around Stn. 1 always shows a divergent condition. The divergence/convergence field in the surface layer and its time scale will be controlled by several oceanographic conditions including internal waves, variable wind fields, river discharge, and so on. Internal waves cause periodical divergent and convergent events in the surface layer with a time scale of the period of them that is not longer than major tidal periods (for example, Stocker and Imberger, 2003). Wind forcing is also a potential reason for divergence and convergence. At Stn. 1, however, buoy experiments were made under different wind condition in different monsoon stages. If the divergent field observed four times at Stn. 1 is a continuous phenomenon over the monsoon period, we could speculate that fresh water plumes from Bangpakong River and/or Chaopraya River maintain the divergence of long time scale. The horizontal distribution of temperature and salinity (Fig. 3) also supports this speculation on such a sustained divergent field, showing that waters discharged from these rivers accumulated around Stn. 1.

Conclusions

The relationship between the divergence/convergence and chlorophyll *a* concentration in the surface layer of UGOT is investigated by field observations of hydrographic properties and experiments using GPS tracked drifters. It is found that there is a clear correlation in a qualitative sense between divergence field and chlorophyll *a*, in which relatively higher chlorophyll *a* is observed in a divergent condition. Such a clear correlation, however, can not be explained by a hypothetical scenario that surface divergence sustains a high chlorophyll *a* concentration in the surface layer by supplying water of high nutrients from the lower layer, having been considered the distribution of nutrients and other hydrographic parameters.

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