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# Upwelling induced by meso-scale cyclonic eddies in the Andaman Sea

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**Abstract**—The results from a survey on oceanographic phenomena and fishery resources in the Andaman Sea, under the Ecosystem-Based Fishery Management in the Bay of Bengal Project, initiated by members of BIMSTEC (the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic cooperation), revealed the evidence of upwelling. It was observed from shallow pycnocline and high salinity near sea surface. The relationship between surface chlorophyll-a (Chl-*a*) and upwelling was prominent that Chl-*a* tended to be high in upwelling areas. Satellite altimetry and the surface geostropic current captured during the same period of the field survey, suggest that upwelling is induced by cyclonic eddies. This phenomenon could be observed on satellite Chl-*a* image over the Andaman Sea. Further investigations are required to assess their role in oceanographic processes, especially primary productivity, in the Andaman Sea.

**Key words:** cyclonic eddy, upwelling, altimetry, geostrophic current, the Andaman Sea, nutrient, chlorophyll

## Introduction

Meso-scale eddies play an important role to induce both horizontal and vertical transports of water masses, heat, momentum, and biogeochemical properties in the sea. In vertical sense, a cyclonic eddy has a potential to induce upwelling in the northern hemisphere, sustain nutrients near the sea surface, stimulate phytoplankton growth and enhance primary productivity in a pelagic ecosystem (McGillicuddy et al., 1998). Fishing potential in such a region becomes high (Onitsuka et al., 2009). Upwelling induced by a cyclonic eddy may be indirectly observed through sea surface temperature, altimetry and surface chlorophyll concentration. They have been reported in several studies such as Tew-Kai and Marsac (2009); Bibby et al. (2008); Chaigneau et al. (2008); Machain-Castillo et al. (2008); Maiti et al. (2008); Reddy and Salvekar (2008); Shanmugam et al. (2008).

The Andaman Sea locates in the northeastern Indian Ocean, surrounded by Myanmar on the north, and Thailand and Malaysia on the east. West of the basin is bounded by the Andaman and Nicobar Island chain (Figure 1). It occupies an area of about $6\times10^5$ km$^2$ and an average depth of about 1,100 m with maximum depth of about 4,400 m in the west (Dutta et al., 2007). The Andaman basin is connected to the Bay of Bengal through the Preparis and Ten Degree Channel, and the Great Channel from north to south, respectively (Sarma and Naverkar, 2001). The area receives large volume of fresh water from the rivers located in the north; one of them is the Ayeyarwady Rivers, the third largest river in the world in terms of suspended sediment discharge (Robinson et al., 2007). Monsoonal climate dominates the entire area–The Northeast or Winter Monsoon during the northern hemisphere winter (December–March), and the Southwest or Summer Monsoon during the northern hemisphere summer (June–September) (Tomczak and Godfrey, 2001).

The Andaman Sea has a potential for offshore fishery such as tuna fishery, which has long been interested by the Fishery Department of Thailand. Compared to the north and the west of the Bay of Bengal, oceanographic conditions in this area have been rarely investigated. There is therefore inadequate scientific information to support sustainable exploitations in fishery resources. To serve this need, an oceanographic survey in the Andaman Sea has been conducted through a collaborative survey named the Ecosystem-Based Fishery Management in the Bay of Bengal, initiated by members of BIMSTEC (the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic cooperation (DOF, 2008). The oceanographic conditions from this survey are investigated and discussed in this present study. Upwelling which was later found to relate to the development of cyclonic eddies, revealed by satellite altimetry during the same period of the field, is also discussed.

## Field observation and data

The oceanographic survey was conducted at 12 stations in the central Andaman Sea (Figure 1) from 6 to 15 November 2007. Salinity and temperature were probed in situ using a Conductivity-Temperature-Depth (CTD) system (Falmouth Scientific Inc.) installed onboard MV SEAFDEC, the research vessel of this cruise. Water depths of the study area are usually greater than 500 meters, but the cable of the CTD system is just 400 meters long. This limitation is not considered to be a problem, since the aim of this study focuses on oceanographic conditions and phenomena near the sea surface. Water samples were collected by using 2.5 liter Go-Flo Niskin bottles attached by a rosette and the CTD system. Chemical parameters including dissolved nitrate plus nitrite ($NO_3+NO_2$–N), dissolved phosphate ($PO_4$–P), and dissolved silicate ($SiO_4$–Si) of water, sampled from 12 depths (0, 10, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400 m), were analyzed onboard using the Integral Futura Continuous Flow Automated Analysis (Alliance Instruments Inc.) (Gordon et al., 1995). Chlorophyll-*a* (Chl-*a*) at 4 depths (2, 10, 125, 250 m) from 9 stations (all stations except Station 1, 2 and 3) were analyzed by using a coloring method on Chl-*a* extracted from the residual on the GF/F filter after water sample filtration (Parson et al., 1984).

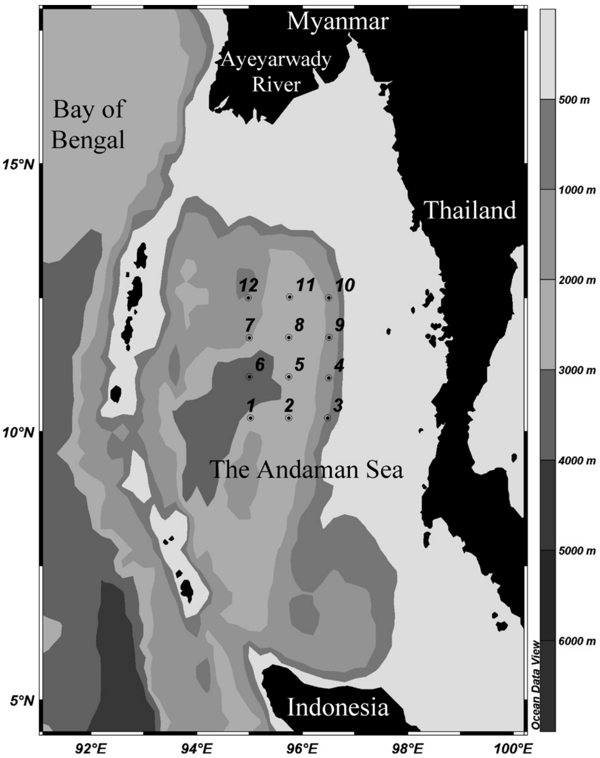


**Fig. 1.** The Andaman Sea, dots showing observational stations.

Satellite altimetry and geostrophic velocity anomalies were obtained from the Ssalto/Duacs system. Data from several altimeter missions including Jason-1&2, Topex/Poseidon, Envisat, Geosat Follow-On (GFO), European Remote Sensing satellite (ERS) 1&2 and Geosat were merged and proceeded to provide 7-day snapshots of the sea-level anomalies and their derived products. Both near real time and delayed data are provided through the AVISO live access server, available at http://las.aviso.oceanobs.com. The data, whose spatial resolution is 1/3 degree, were used to obtain the spatial structure of eddies, which were then compared and discussed with the oceanographic data from field observation. Both satellite and oceanographic data were graphically analyzed using Ocean Data View software (Schlitzer, 2005).

## Distributions of seawater parameters

Surface distributions of salinity and density (sigma), measured during the field observations (Figure 2), indicate zones of different water characteristics between the southwest and the north or the northeast of the study area. Salinity and sigma in the southern zone ranged 32–33 psu and 20 kg/m$^3$ while those in the northern zone were around 31 psu and 19 kg/m$^3$, respectively. Temperature distribution also had this trend, but its ranges were narrow to about 28.25–28.75°C. Meanderlike contours lining in northwest-southeast direction are prominent in the distribution figures of salinity and density. Vertical distributions of physical water proper-

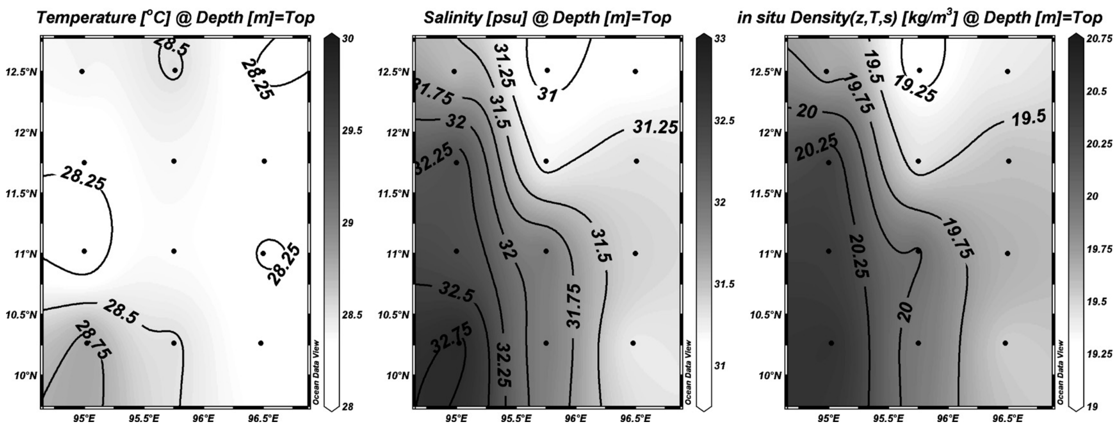


**Fig. 2.** Horizontal distributions of temperature, salinity, and in-situ density (sigma) at the sea surface.

ties along the westernmost transect line (Station 1, 6, 7 and 12) are shown in Figure 3. Thermocline located at around 100–150 m depth while halocline was shallower (80–100 m depth), resulting in wide ranges of pycnocline of about 80–150 m depth. Upwelling in the south was observed from shoaling of contour lines. This phenomenon is related to the area of distinct water characteristics in the southwest corner of the study area in Figure 2.

Concentrations of dissolved inorganic nutrients, including nitrate+nitrite, phosphate and silicate, at 10 m depth were not high in the southwest area (Figure 4) where the upwelling occurred. High nutrient area, however, did not exist in the same way as in the case of the distributions of salinity and density. Most nutrients data near the sea surface at station 1 were not available; therefore, we decided to remove the southern line (Station 1, 2 and 3) off the ODV contour plots to minimize misinterpretation on nutrient distribution due to extrapolation. Nitrate+Nitrite concentrations at the sea surface of most stations were in the levels of undetected by the analytical instrument and were not presented in Figure 4. Phosphate concentrations at 10 m depth were in ranges of 0.4–0.5 μM while those of silicate were in 0.5–1.5 μM. Vertical distributions of nutrients along the westernmost transect line (Station 6, 7 and 12) (Figure 5) do not indicate a trend of upwelling as those of physical properties (Figure 3). Nutrient concentrations were very high at great depth and very low near the sea surface with nutriclines located at around 100–200 m depth.

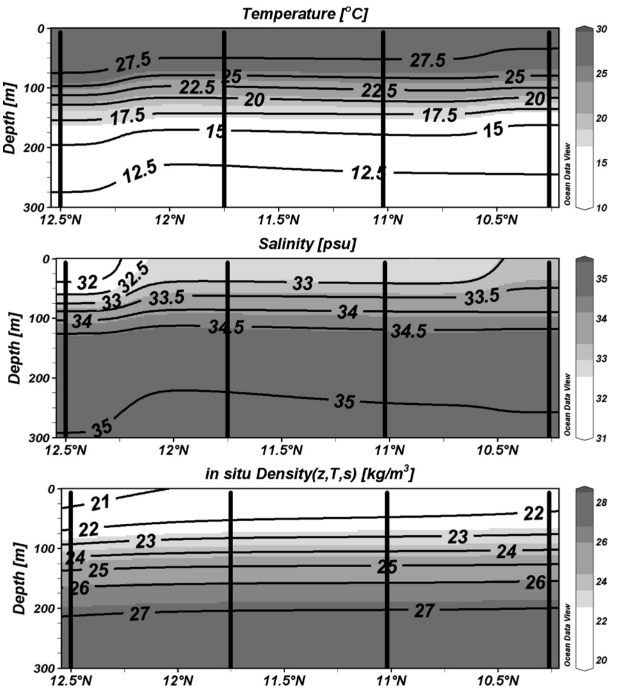


**Fig. 3.** Vertical distributions of temperature, salinity, and in-situ density (sigma) along the west transect line.

Surface Chl-*a* (Figure 6) was high in the upwelling region (Figure 2 and 3) although nutrients near the sea surface were not. It should be noted that Chl-*a* data from all southernmost stations (Station 1, 2 and 3) are not available because of a technical problem during the processes of seawater analysis. High Chl-*a* in both the southwestern and the southeastern corners, where nutrients were not significantly high, are supposed to occur in a phase when nutrients were depleted due to uptake of phytoplankton. This issue is discussed in detail in the following section.

## Discussions

Merged figures of seven days averaged satellite altimetry and their derived surface geostrophic circulation anomaly (Figure 7) reveal a coincidence of cyclonic eddy development, the upwelling and high surface Chl-*a* area (Figure 2, 3 and 6). This suggests that upwelling, obviously observed in the southwest of the area, be induced by such a surface circulation resulting in relatively high surface Chl-*a*. The same phenomena is used to explain high Chl-*a* in the southeastern area (Figure 6) where a weak cyclonic eddy exist around there. Moving speed of the eddy, located just in the southwest of the study area (Figure 7), is estimated based on Rossby

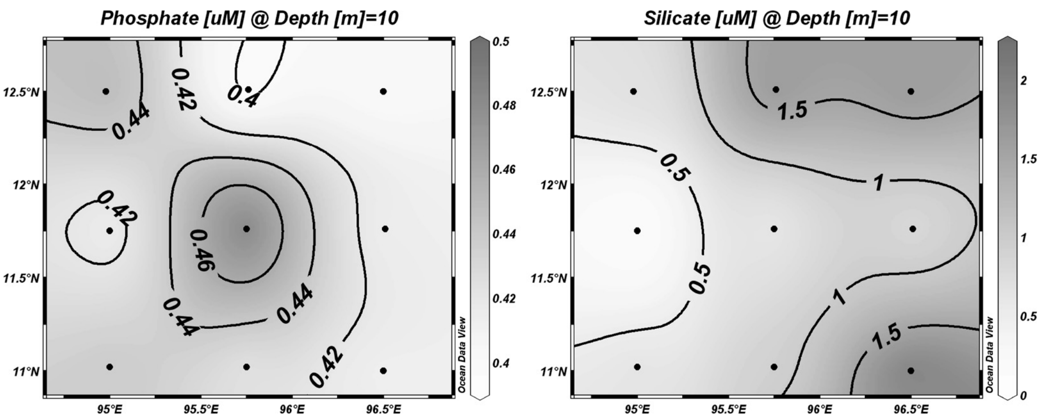


**Fig. 4.** Horizontal distributions of phosphate and silicate near the sea surface (10 m depth).

wave's theory (Pond and Pickard, 1983). For simplicity, it is assumed that the eddy is forced just in barotropic mode and its moving speed ($\omega$) can be estimated by Equation 1.

$$\omega = \frac{\beta}{k^2} \quad (1)$$

where $\beta = \partial f / \partial y$; $f$ is Coriolis's parameter ($2\Omega \sin\varphi$); $\Omega$ is angular velocity of Earth's rotation ($7.29\times10^{-5}$ rad/s); $y$ is meridional distance (m); $k$ is wave number ($2\pi/L$); $L$ is the wave length (eddy radius×2) ($\sim1.5\times10^{5}$ m). Substitute all parameters, extracted from Figure 7, into Equation 1 yields the eddy moving speed of about 0.04 m/s or 3.5 km/day.

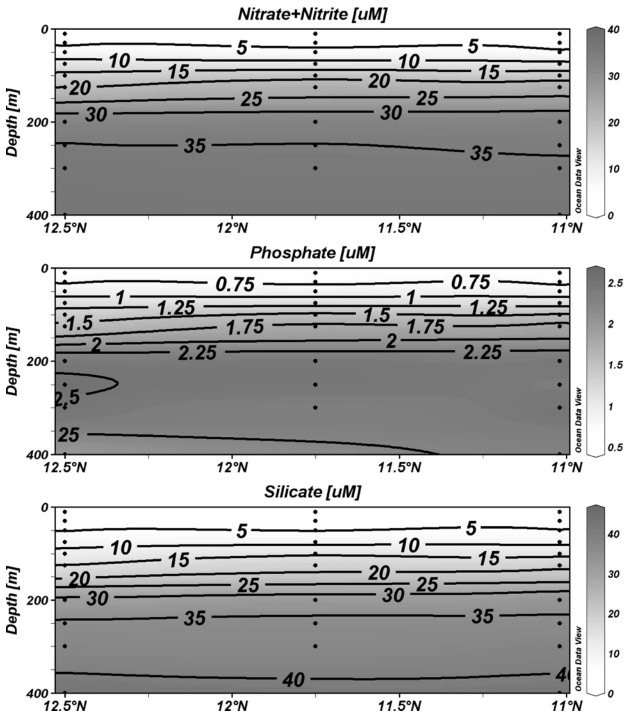

**Fig. 5.** Vertical distributions of nitrate+nitrite, phosphate and silicate along the west transect line (except Station 1).

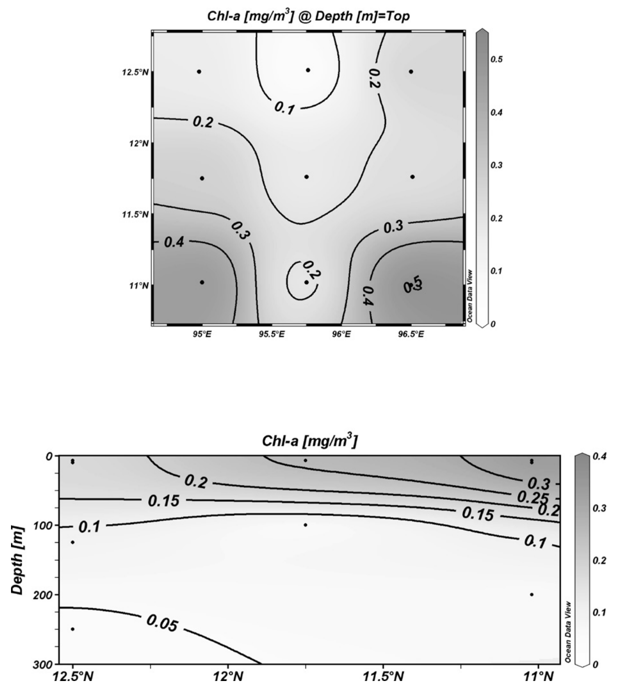

**Fig. 6.** Horizontal distribution at sea surface and vertical distribution along the west transect of Chl-*a*.

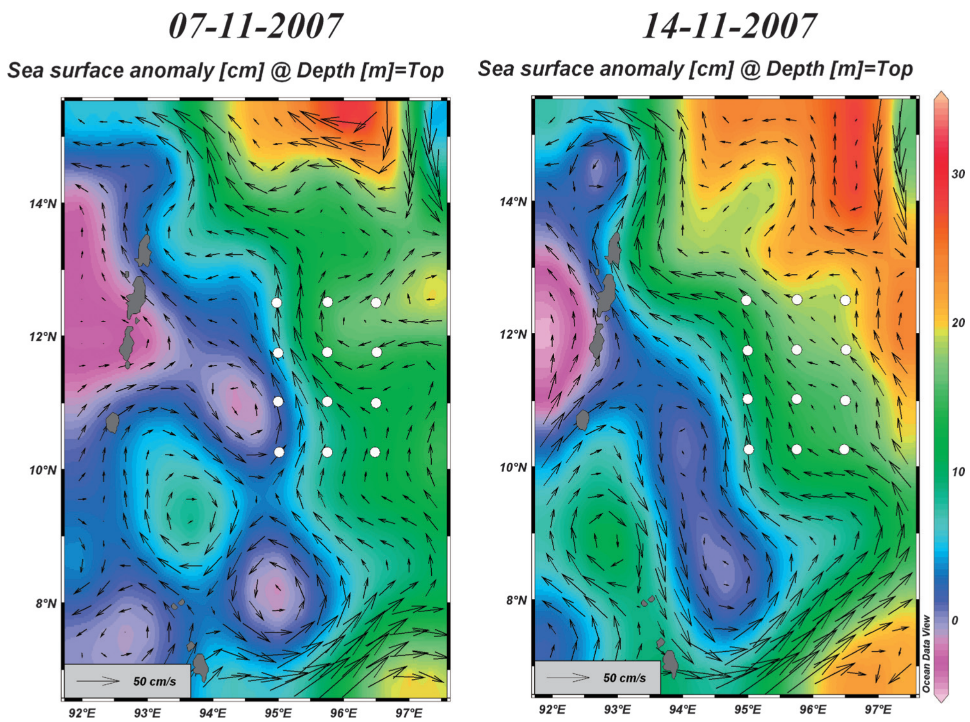

**Fig. 7.** Seven-days merged satellite altimetry, centered on November 11, 2007 and November 14, 2007, and their surface geostrophic current anomalies.

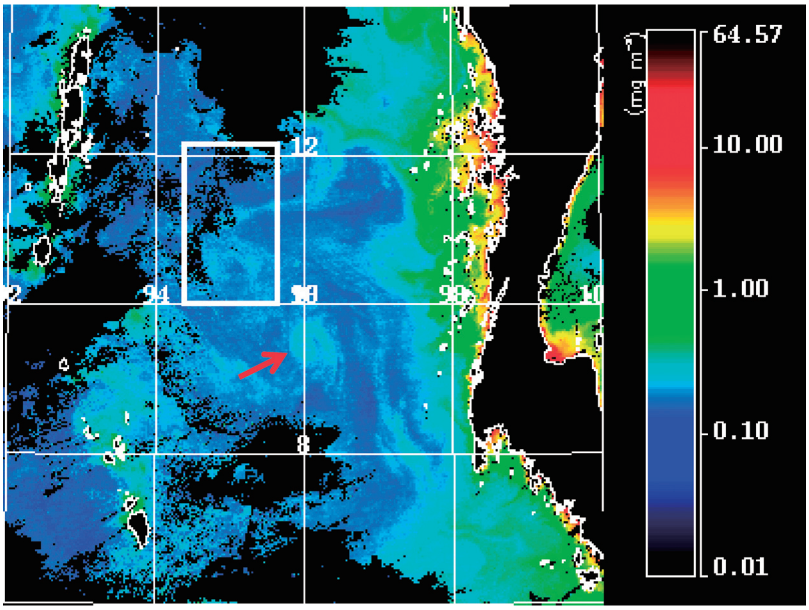


**Fig. 8.** MODIS-Chl-*a* image captured on November 29, 2007 showing an example of a Chl-*a* whirlpool (red arrow) developed in the Andaman Sea. A white frame represents boundary of the field observation.

Compared to its radius (150 km), this moving speed is quite slow, providing times for phytoplankton to use upwelled nutrients for photosynthesis due to short phytoplankton regeneration rate (Dickson and Wheeler, 1995). Because the upwelling is weak (3 m uplift in 10,000 m distance, estimated from Figure 3), it can pump nutrients from just shallow subsurface layer that may be sufficient to stimulate phytoplankton growth, but their amount may not sustain and easily depleted. This is used to explain why we observed high Chl-*a* but low nutrients in upwelling areas.

Low, mostly undetectable, dissolved inorganic nitrogen (DIN), in terms of Nitrate+Nitrite, near the sea surface suggests that it may play an important role as a limiting nutrient to pelagic primary productivity in the Andaman Sea. Although role of dissolved Fe to phytoplankton productivity in other areas, especially the open oceans, has been focused in many studies (e.g., Seeyave et al., 2007; Kudo et al., 2005), it has not been reported for the Andaman sea. This suggests the need of further investigations on this issue.

Surface water temperature is usually low where an upwelling occurs, but it is high in this study (Figure 2). It is possible that this evidence was resulted from temporal variations of surface temperature because the cruise took 10 days to complete. Daily variation in weather condition may be the cause of this evidence. Surface water temperature gradient is small, due to tropical characteristic, and therefore small changes can be prominently observed. Moreover, vertical distributions of physical water properties (Figure 3) suggest that vertical gradient of salinity near the sea surface is larger than that of water temperature. Weak upwelling, therefore, can trigger high salinity, not low water temperature, in surrounding region.

Cyclonic eddies, found in altimetry images, were compared with surface Chl-*a* derived from Moderate-Resolution Imaging Spectroradiometer (MODIS) data. Unfortunately, MODIS data during the period of field observation were not available due to cloudiness. A Chl-*a* image in a later time within the same month is then used for discussion instead. A whirlpool of relatively high Chl-*a* is observed in a MODIS imagery captured on November 29, 2007 (Figure 6). Chl-*a* in the whirlpool was as high as 0.2–0.3 $mg/m^3$ while that in surrounding water was lower than 0.1 $mg/m^3$. This phenomenon may be used to confirm the existence of upwelling induced by cyclonic eddies in this area.

Systematic investigation on oceanographic condition and lower trophic level ecosystem should be conducted to clarify the processes, such as, eddy development, upwelling, and pelagic productivity in the Andaman Sea. Although upwelling induced by meso-scale cyclonic eddies found cannot trigger very high Chl-*a*, they are considered as a significant supporter to enhance primary productivity in oceanic surface water if there are a lot of them develop and remain for several weeks. Further investigations on roles and contributions of this phenomenon to pelagic ecosystem in the Andaman Sea are strongly required.

## Conclusion

Measured oceanographic data in the Andaman Sea from 6 to 15 November 2007 revealed the occurrence of upwelling, resulting in high Chl-*a* in surface water around the incident area. Such a phenomenon was proved to be triggered by a cyclonic eddy, revealed by satellite altimetry and geostrophic current anomaly, developed at the same time. A MODIS Chl-*a* image, retrieved in the same month of field observation, illustrates a whirlpool of high Chl-*a*, which may be used to confirm the development of upwelling induced by cyclonic eddies revealed by this study.

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