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WATER CHARACTERISTIC IN THE SOUTH ANDAMAN SHELF SEA FROM OBSERVATIONS DURING 2014–2019

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ABSTRACT: Temperature and salinity are typically used to describe the characteristics of water masses in the ocean. In the South Andaman Shelf Sea (SASS), the Department of Marine and Coastal Resources in Thailand has regularly conducted measurements of these variables using Conductivity-Temperature-Depth (CTD) twice a year during pre- and post-Northeast Monsoon (NEM) seasons since 2014. In this paper, we analyzed the measured data to describe water characteristics in the SASS. Our analysis suggests that SASS waters are typically less dense during the pre-NEM season; a result which is largely attributed to low-salinity water. We propose that this effect is due mainly to local discharges along the west coasts of Thailand and Malaysia. At the peak of the NEM season, local rivers continue supplying fresh water to the coastal sea. This supply mixes with ambient waters and is transported northward. This fresh water particularly influences the southern SASS waters. As a result, salinity differences between the northern and southern SASS becomes larger during the post-NEM season. In addition to these general characteristics, observations also showed signs of coastal upwelling along the Thai coast in the vicinity of Phangnga, in 2014.

Keywords: South Andaman Sea, Shelf Sea, water characteristic, coastal upwelling

INTRODUCTION

The Andaman Sea (AS) is a marginal sea in the East Indian Ocean. Geographically, the sea is separated from the Bay of Bengal in the northeastern Indian Ocean, by an island chain (the Andaman and Nicobar Islands) with multiple channels running from Sumatra in the south to Myanmar in the north. The Andaman Sea is bordered by Myanmar and the Malaysian Peninsula to its east and is connected to the South China Sea through the Malacca Strait to the south. Along the sea boundary, connections through multiple channels enable water mass exchange between the Indian Ocean and freshwater discharge from the continent which freshens up the upper-layer of the AS water annually. This results in variation in water properties spatially. In this study, we focus on the South Andaman Shelf Sea (SASS) adjacent to the southwestern part of Thailand (Fig. 1). Since the area is connected to the Malacca Strait, we expect Strait throughflow to influence water mass characteristics in this region which should be apparent in our observations.

Precipitation is high during Southwest Monsoon (SWM). This adds a considerable amount of fresh water to the coastal sea especially along the northeastern to eastern margin of Bay of Bengal and Andaman Sea (Sengupta *et al*. 2006; D'Addezio *et al*. 2015; Pant *et al*. 2015; Mahadevan *et al*. 2016). Fresh water is then delivered offshore through mechanism-like instability. The fresh water mass mixes with ambient waters, and decreases the upper-layer salinity seasonally (Mahadevan *et al*. 2016). Low-salinity water is then transported southwards partially to the South Andaman Sea, especially during the transition from SWM to NEM seasons via the surface current (Mahadevan *et al*. 2016; Chatterjee *et al*. 2017; Kiran 2017). This freshening can also vary interannually responding to large-scale variability caused by the Indian Ocean Dipole and El Nino Southern Oscillation (Pant *et al*. 2015). Together with local discharges, we expect relatively cold fresh water in the SASS during this period of a year.

Presumably driven by an along-strait pressure gradient (Li *et al*. 2015), Malacca Strait throughflow is prominent during the NEM season (Wyrki 1961). This is when the northerly winds raise sea level inducing southward running currents along the eastern coast of the Malaysian peninsula (Daryabor *et al*. 2016), with the same wind inducing offshore transport and lowering sea level along the western coast annually (Clarke and Liu 1992). Growing sea level differences between the two sides of the strait induces northward transport according to dominant terms in along-strait momentum balance (Li *et al*. 2015). Since precipitation in Malacca Strait is high until December (Tan *et al*. 2006; Wong *et al*. 2016), it continually supplies fresh water to the strait which promotes northward transport of plume water and subsequently freshens shelf water up to a certain latitude (see fig. 3 in Amiruddin *et al*. 2011).

As the plume water is typically enriched by nutrients, this should promote high productivity in southern SASS. Based on satellite observations, Tan *et al*. (2016) show high productivity in the Malacca Strait during the NEM, but they suggested that it is mainly due to Ekman pumping. We believe that the along-strait pressure difference and buoyancy-driven flow along the eastern boundary which in turn induces northwards transport also play significant roles. As seen in figure 2 of Tan *et al*. (2016), the area of high chlorophyll concentration is trapped along the eastern boundary corresponding to the general dynamics of a buoyancy-driven coastal current (see Garvine 1998; Fong and Geyer 2002).

In this study, we analyzed the data obtained from a Conductivity-Temperature-Depth (CTD) instrument in order to examine the water characteristics on the South Andaman Shelf. In reporting our results we first provide details of the datasets used in our analysis before showing vertical profiles, and temperature-salinity diagrams which describe physical properties of SASS waters during monsoon transitions. Some special features such as coastal upwelling are also discussed prior to a concluding paragraph.

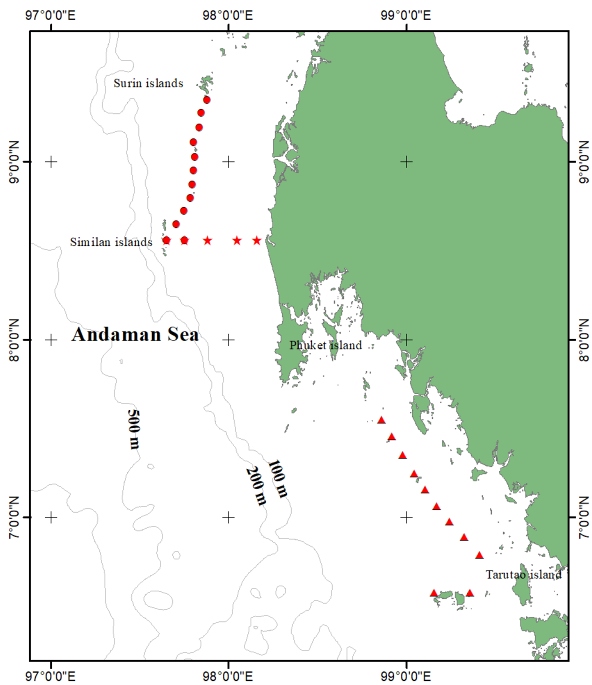


Figure 1. Map illustrating locations for CTD casts along routes; route A (solid circles), route B (solid triangles), and route C (stars).

MATERIALS AND METHOD

Compact CTD, models JFE ASTD687 and Rinko profiles ASTD102, were casted along three transects (A, B, and C) on the South Andaman Shelf (Fig. 1). Transect A lies between Surin and Similan Islands and Transect B is between Phuket Island and Tarutao Island. We used measurements collected along Transect A to describe general properties of the water mass in the northern SASS and used B for the properties in the southern SASS. Transect C lies across the shelf from the Similan Islands to the Phangnga coast. Observations were recorded twice a year during the two monsoon transitions. The first transition is from SWM to NEM (November) hereafter in this paper called pre-NEM season, and the latter transition is from NEM to SWM (March-May) hereafter called post-NEM season (see Table 1 for observation periods).

Temperature and salinity are typically used to describe water properties in the ocean as they are considered conservative properties altered mainly by physical processes. Thus, we used in situ temperature and practical salinity from CTD and converted them into conservative temperature (Θ) and absolute salinity (S_A) using the Gibbs SeaWater oceanographic toolbox (McDougall and Barger 2011). The readers may find definitions for these converted factors in the International thermodynamics equation of sea water 2010 (IOC, SCOR and IAPSO 2010). Density referred to in this paper is sigma-0 (σ_0) calculated by subtracting potential density referenced to zero pressure with 1000 kg/m^3. Therefore, variables later reported in this paper refer to Θ , S_A and σ_0 . We note that S_A is slightly greater than practical salinity, so the reader should be cautious when citing the results in this study.

To have an analysis on costal upwelling observed in 2014, we also collected daily wind reanalysis from the National Center for Environmental Prediction (NECP) which is produced under the NCEP/NCAR Reanalysis 1 project. The project uses a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present (Kalnay *et al*. 1996). The data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at https://www.esrl.noaa.gov/psd/.

Table 1. Observation periods in the northern SASS and southern SASS during 2014-2019

Periods	Northern SASS	Southern SASS
Pre-NEM season	17-20 Nov 2014	04-06 Nov 2014
	09-13 Nov 2015	24-26 Nov 2015
Post-NEM season	17-20 Apr 2014	05-08 May 2014
	06-08 Mar 2017	21-23 Mar 2017
	24-26 Apr 2018	07-09 May 2018
	7-10 Apr 2019	24-26 Apr 2019

RESULTS AND DISCUSSION

Salinity

Figure 2 illustrates changes in averaged salinity with respect to depth in South Andaman Shelf Sea separated into northern and southern SASS during pre- and post-NEM seasons. During the first period, salinity in northern SASS (southern SASS) varied from 31.83±0.33 (31.45±0.25) near the surface to 32.88±0.41 (33.12±0.38) at 39 m (Fig. 2a). In the post-NEM season, salinity uniformly increased from 32.83±0.25 (32.06±0.48) near the surface to 33.47±0.22 (33.33±0.49) at 39 m. Compared to the post-NEM season the salinity was generally lower in this region. We suggest that freshening is due to southward propagation of low-salinity water from the North Andaman and local freshwater discharge as explained in the first part of the introduction.

Sea water is typically fresher in the southern SASS than in the northern SASS. Figure 2 shows that near-surface salinity was about 0.38 lower during the pre-NEM season (0.77 for the post-NEM season), and Figure 3 shows that the salinity uniformly declined from north to south during the post-NEM season. We speculate that this is possibly due to the fact that Transect B lies closer to the coast, which causes local freshwater discharge to influence the observation, but past study showed that near-surface salinity was similarly reduced towards the Malacca Strait (see figure 5b in Rama Raju *et al*. 1981). It is also noticeable that the difference grows larger during the post-NEM season and remains so down to 40 m (Fig. 2b). If local fresh water were to play a role in this freshening, we might expect larger salinity differences during the pre-NEM season rather than the post-NEM season as local discharge could be more influential to Transect B. How can this be? Our thinking is as follows.

Pressure differences between the two sides of the Malacca Strait can be more prominent during the NEM season as monsoonal wind raises sea level along the western SCS boundary, but causes offshore transport and lowering of sea level along the eastern AS. This induces northward transport through the Malacca Strait. As the current flows toward the north, plume water along western coast of Malaysia is transported along with it. As a result of Coriolis influence the plume water tends to be close to the eastern boundary where it mixes with ambient water downstream.

Temperature

Similar to Figure 2, Figure 4 displays temperature profiles in South Andaman Shelf Sea during pre- and post-NEM season. Vertically, temperature was nearly-homogenous in the upper 20 m (29.88±0.67 ºC in northern SASS and 30.42±0.67 ºC in southern SASS) during the pre-monsoon season. The profile is, however, tilted about 18-20 m during post-NEM season suggesting relatively warm temperature in the upper 18 m but cold water below such a depth. Our explanation for such a pattern is as follows. Net downward surface heat flux warms near-surface

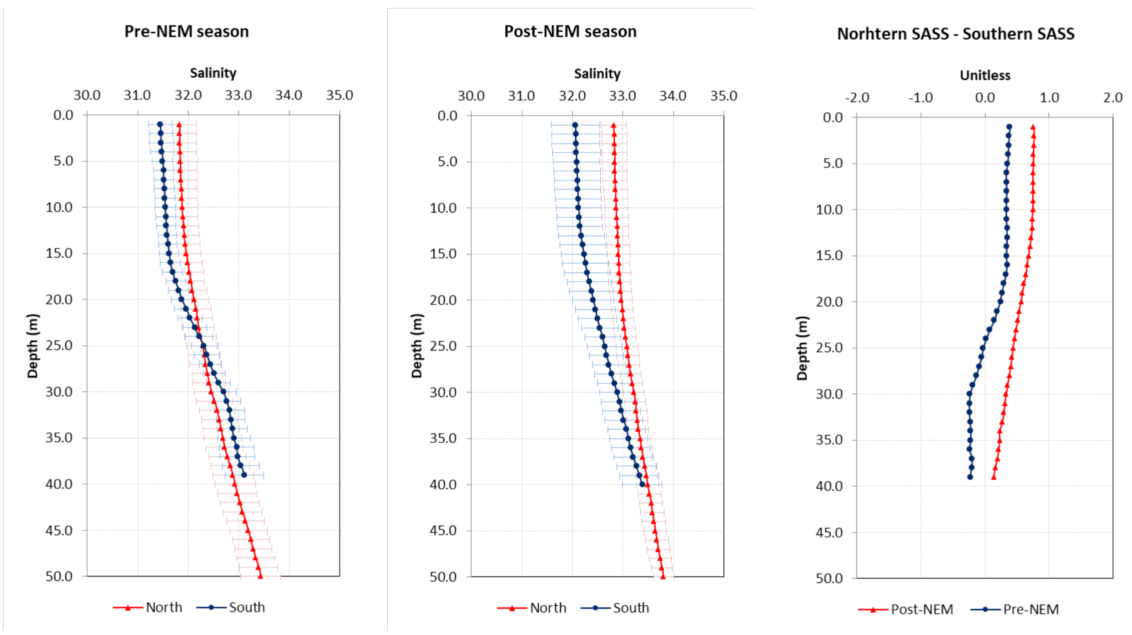


Figure 2. Change in averaged salinity with respect to depth and its standard deviation (error bars) during pre-NEM season (left panel) and post-NEM season (middle panel) averaged along routes in the northern South Andaman Shelf Sea (SASS) (line with solid triangles), and in the southern SASS (line with solid circles) in 2014, 2018, and 2019, and difference in salinity between the northern SASS and the southern SASS (right panel) during pre-NEM season (line with solid circles) and post-NEM season (line with solid triangles).

water during March-May, and coastal sea level is relatively lower during the NEM season than during the SWM season which is associated with a shallower thermocline depth. Together with large amplitude internal waves that typically occur during January-May, it promotes mixing and causes reduction in subsurface water temperature efficiently (see, *e.g.*, Osborne and Burch 1980; Schmidt *et al.* 2016; Magalhaes and Da Silva 2018). As a result, we observe relatively warm water overlying cold water during this period of a year.

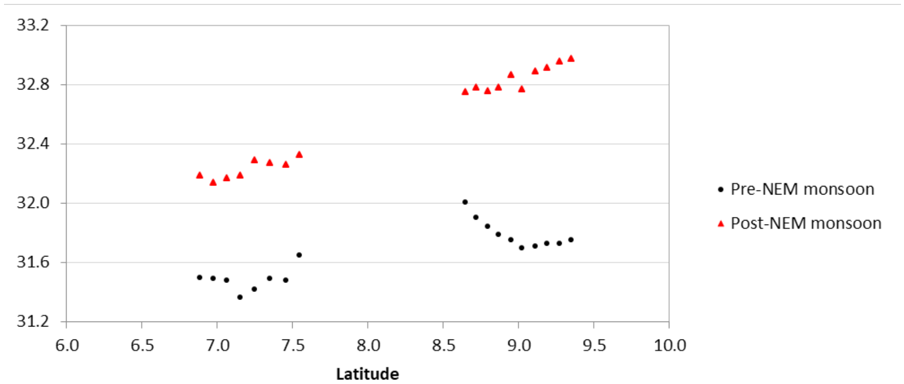


Figure 3. Depth-averaged salinity in the upper 10 meters averaged for all observation periods from north to south during pre-NEM (solid circles) and post-NEM season (solid triangles).

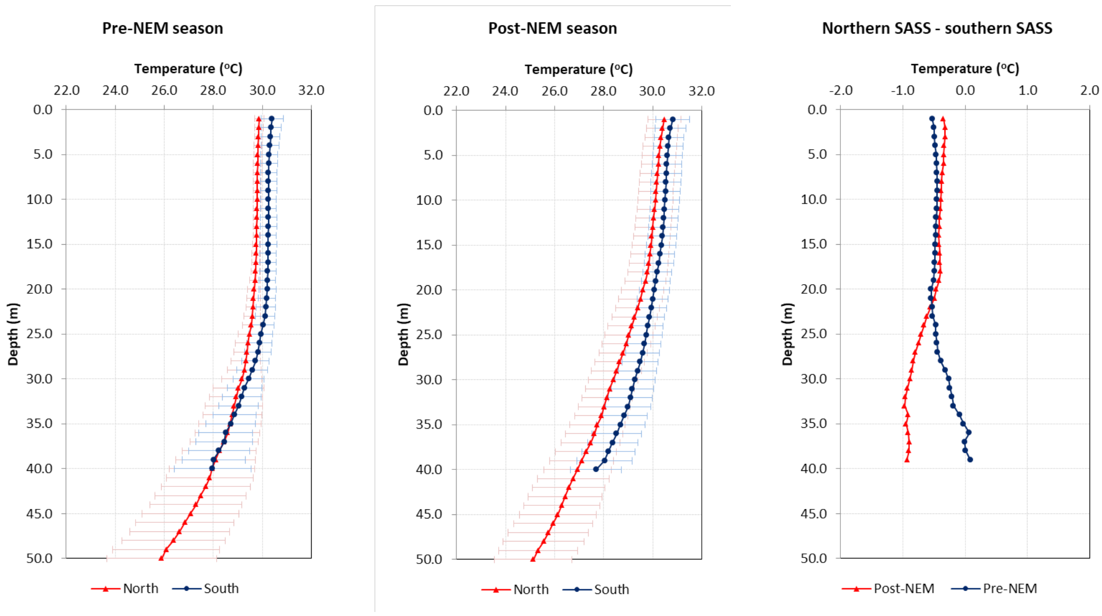


Figure 4. Change in conservative temperature with respect to depth with standard deviation (error bars) during pre-NEM season (left panel) and post-NEM season (middle panel) averaged along routes in the northern South Andaman Shelf Sea (SASS) (line with solid triangles), and in the southern SASS (line with solid circles) in 2014, 2018, and 2019, and difference in temperature between the northern SASS and the southern SASS (right panel) during pre-NEM season (line with solid circles) and post-NEM season (line with solid triangles).

Density

Figure 5 shows potential density referenced to zero pressure. We note again that density reported in this paper is actually sigma-0 calculated by subtracting potential density with 1000 kg/m^3. In the pre-NEM season, density in the in northern SASS (southern SASS) increased from 19.3±0.3 kg/m^3 (18.9±0.3 kg/m^3) near the surface to 20.7±0.8 kg/m^3 (20.9±0.7 kg/m^3) at 39 m. In the post-NEM season, density increased uniformly and varied from 19.9±0.3 kg/m^3 (19.2±0.4 kg/m^3) near the surface to 21.4±0.5 kg/m^3 (21.0±0.6 kg/m^3) at 39 m. In both periods, density was quite homogenous in the upper 15 m. It was deeper during the pre-monsoon season than the later monsoon season.

Compared to the northern SASS water, the southern SASS water was slightly less dense especially during the post-NEM season (about 0.7 kg/m^3 near the surface). It was also noticeable in Figures 2 and 5 that the variation of the density with depth resembled that of salinity. Such results suggest that salinity dominates density variation in this region. By using a linear equation of state, we approximate that about 69% of the change in density is due to salinity variation.

Coastal upwelling in 2014

Coastal upwelling along the eastern boundary can be induced when northerly winds persist for a certain period of time. The winds induce offshore transport near the surface due to Ekman transport but onshore transport near the bottom due to modified bottom pressure gradients. On April 17, 2014, we noticed coastal upwelling that was associated with the positive tilt of isothermal and isohaline contours off Phangnga's coast (Fig. 8 upper left and 8 upper right) along Transect C (Fig. 1), but we did not observe such a pattern in March 2017 (Fig. 9 upper left and 9 upper right). NCEP wind reanalysis showed that northerly winds blew along the coast and persisted for longer than a week before the observation on April 17, 2014 (Figs. 8 and 10). However, winds were gentle (2 m/s) and the directions were quite variable in 2017 (Figs. 9 and 10). We note that this is still not conclusive answer to the costal upwelling observed in 2014 though this preliminary result is supportive to our field observation. Thus, more study on Andaman coastal upwelling might be an interesting topic for future study.

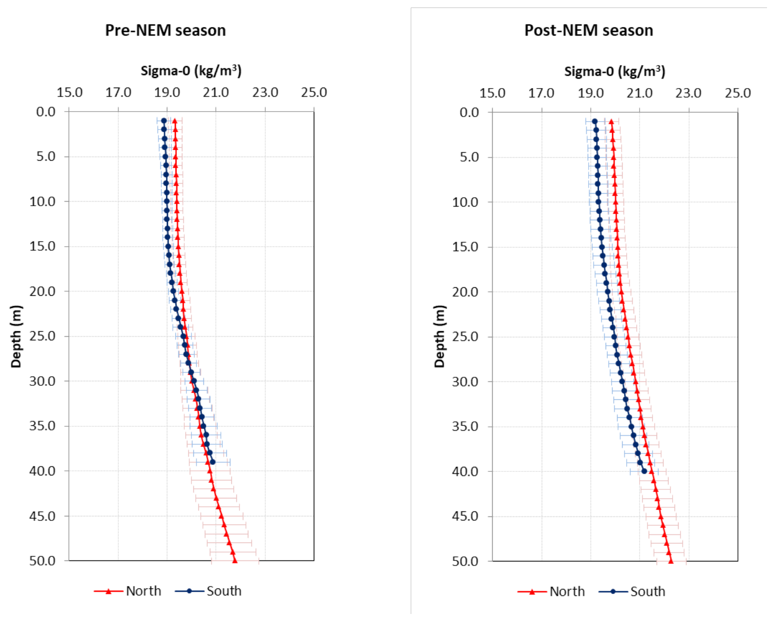


Figure 5. Change in potential density with respect to depth with standard deviation (error bars) during pre-NEM season (left panel) and post-NEM season (right panel) averaged along routes in the northern South Andaman Shelf Sea (SASS) (line with solid triangles), and in the southern SASS (line with solid circles) in 2014, 2018, and 2019.

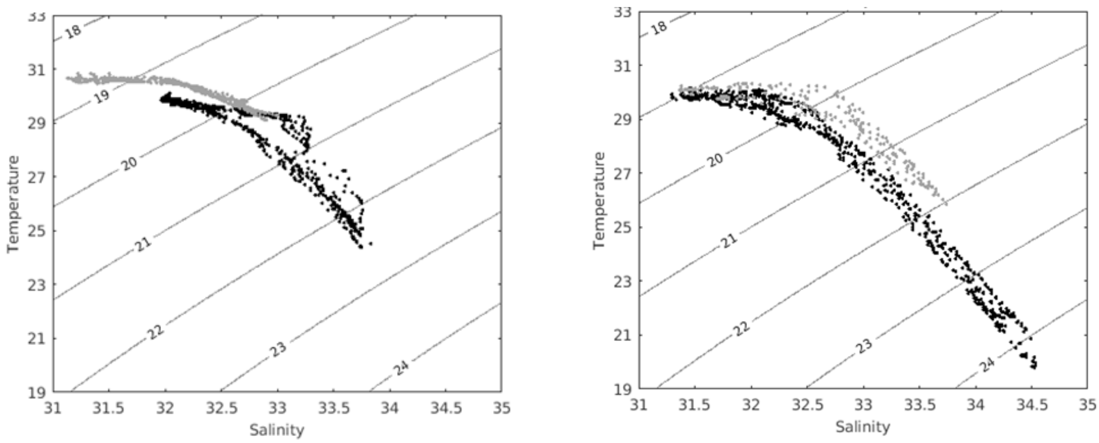


Figure 6. Temperature-salinity diagram plotted from observations in the northern South Andaman Shelf Sea (SASS) (black dots) and southern SASS (gray dots) during pre-NEM season in 2014 and 2015.

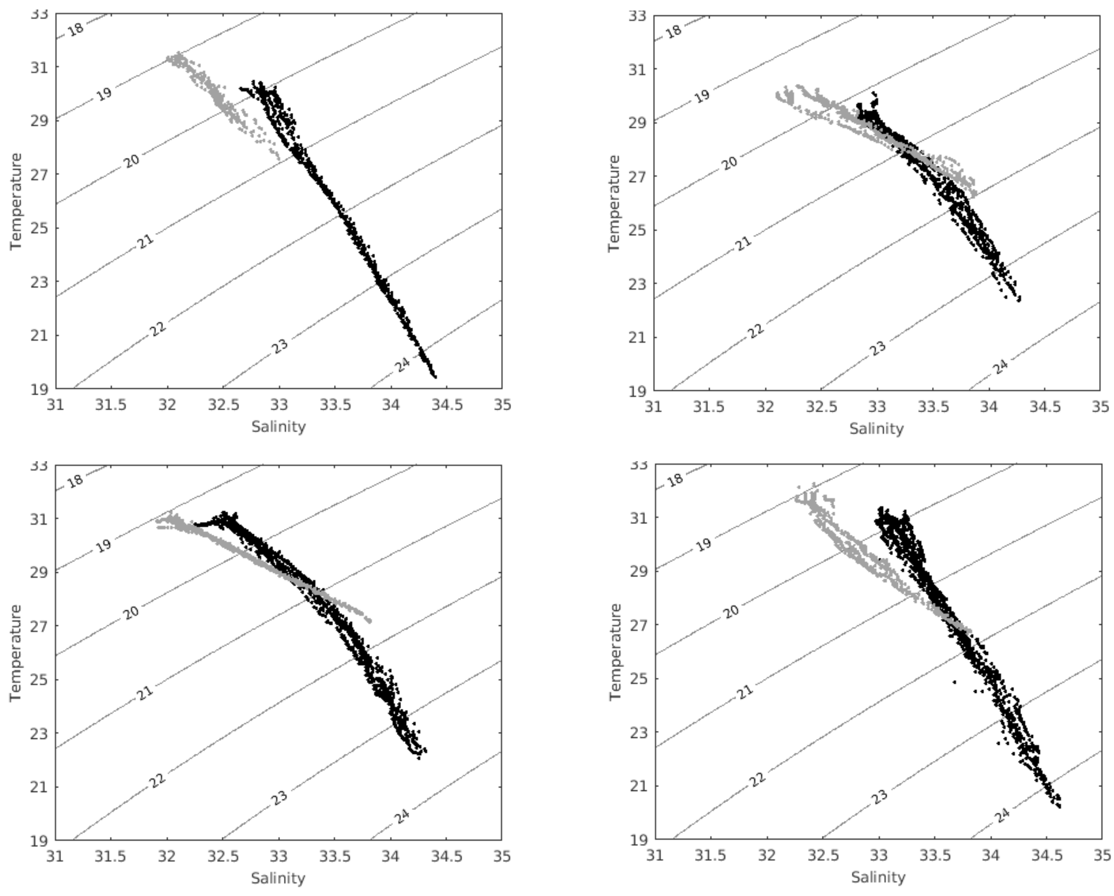


Figure 7. Temperature-salinity diagrams plotted from observations in the northern South Andaman Shelf Sea (SASS) (black dots) and southern SASS (gray dots) during post-NEM season in 2014, 2017, 2018, and 2019.

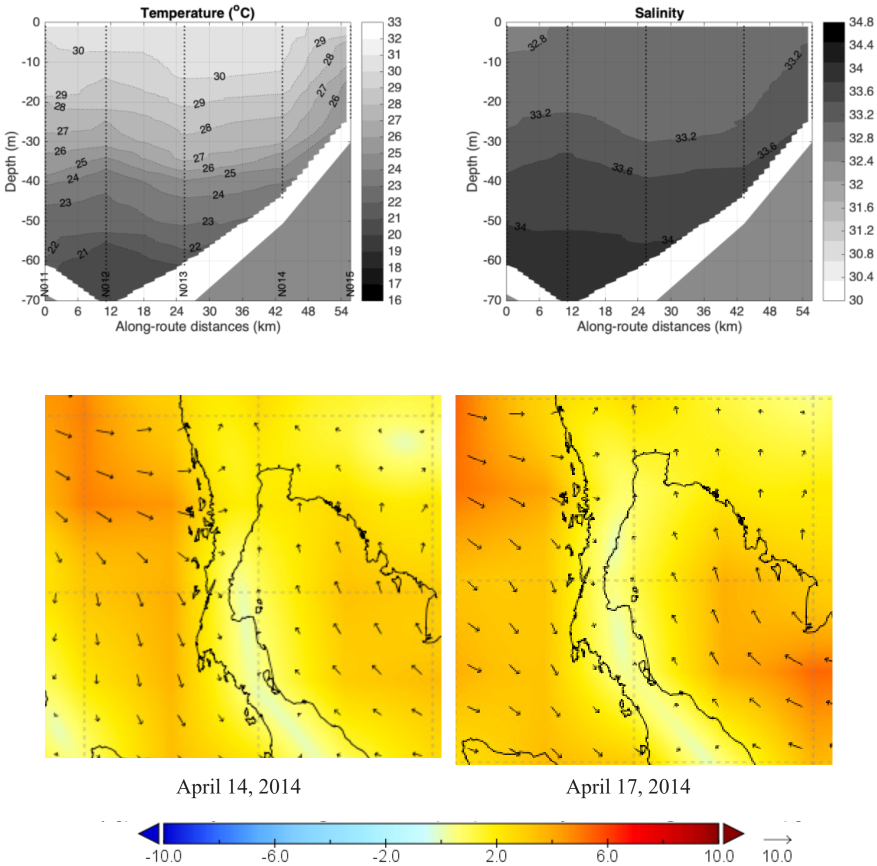
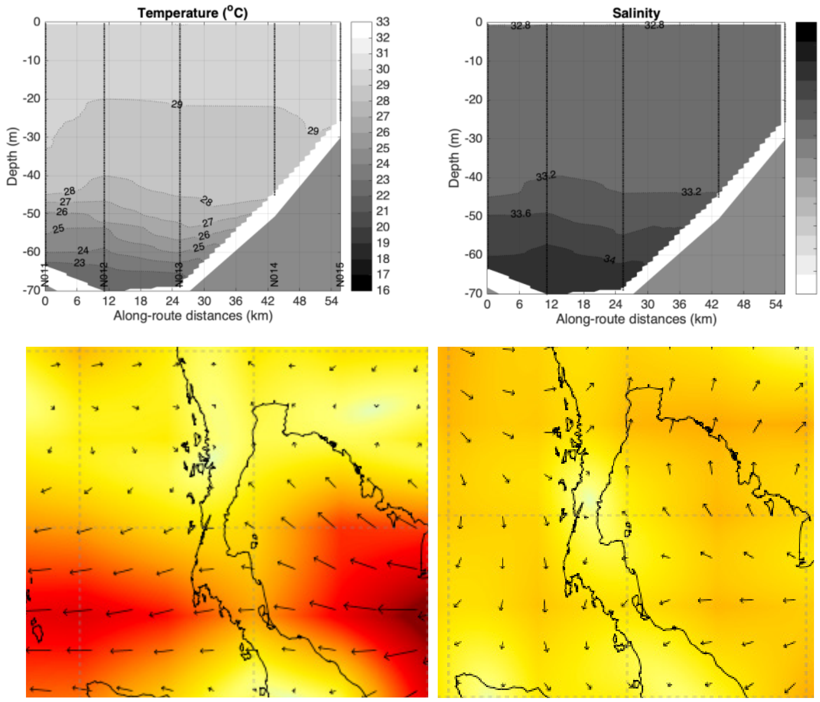


Figure 8. Vertical structure of temperature (upper left) and salinity (upper right) along transect off Phangnga's coast (see star in Figure 1) collected on April 17, 2014, and wind speed (m/s) and direction 3-day before and during observations (lower left, lower right).

CONCLUSION

The South Andaman Shelf Sea is recognized as an important area with high productivity in the region. The Department of Marine and Coastal Resources in Thailand have regularly conducted measurements using Conductivity-Temperature-Depth (CTD) twice a year during pre-NEM and post-NEM seasons. Observations show that SASS water is typically fresher during the pre-NEM season. This freshening can be due to local freshwater discharge. During the post-NEM season, local freshwater discharge and northward transport of plume water, however, characterize water properties in the southern SASS. Our approximation suggests that about 69% of the density difference is attributed to salinity difference which leads to lower density of southern SASS water.

In addition to the above characteristics, coastal upwelling was observed in 2014. This can be induced by short-time persistence of northerly winds along the eastern Andaman Sea boundary as it induces offshore transport near the surface but onshore transport near the bottom. NCEP wind data agree with our explanation of this effect showing persistent northerly winds a week before the observation period in 2014.



March 3, 2017 March 6, 2017

Figure 9. Vertical structure of temperature (upper left) and salinity (upper right) along transect off Phangnga's coast (see star in Figure 1) collected on March 6, 2017, and wind speed (m/s) and direction 3-day before and during observations (lower left, lower right).

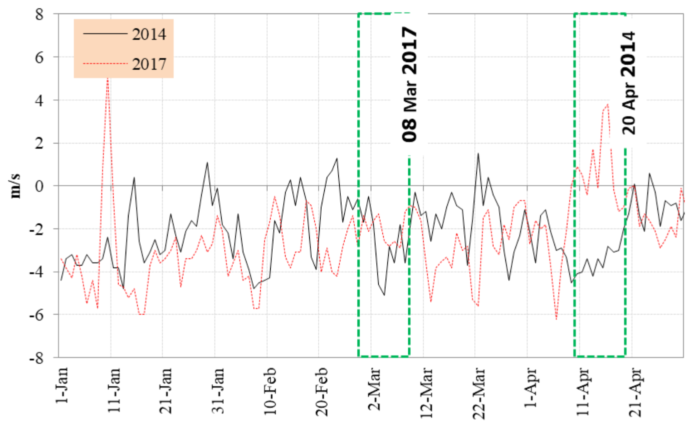


Figure 10. Meridional component of wind at 10°N 97.5°E in 2014 and 2017.

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