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SEASONAL CHARACTERISTICS OF THE SEA SURFACE TEMPERATURE AND SEA SURFACE CURRENTS OF THE STRAIT OF MALACCA AND ANDAMAN SEA

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Abstract: This study presents 33 years (1982-2014) of satellite-derived sea surface temperature (SST) data on the Strait of Malacca and Andaman Sea obtained from the Advanced Very High-Resolution Radiometer. The data on sea surface currents data were obtained from the global ocean model, the Hybrid Coordinate Ocean Model. Since the area that was studied is influenced by Asian monsoons — the Northeast and Southwest Monsoons — this study aims to describe the seasonal variations of SST and current circulation in the region. The seasonal SST from this study showed that the SST of the Strait of Malacca was warmer than the Andaman Sea during the Southwest Monsoon. The current circulation during both seasons flowed north-westward. The special feature found in this study is the formation of a seasonal thermal front during the Southwest Monsoon. It was based on the calculation of the horizontal SST gradient between two transects in the Andaman Sea and the Strait of Malacca. The temperature was warmer in the Strait of Malacca and cooler in the Andaman Sea due to prevailing winds that bring heavy precipitation to the region. This study provides useful information on the Strait of Malacca and Andaman Sea that may be important for Malaysia's future climate and weather predictions.

Keywords: AVHRR, SST, asian monsoon, surface current, thermal front.

Introduction

Studies on seawater temperatures and current circulations are fundamental in understanding the dynamics of the ocean. Previous studies through historic data had shown that the evolution of ocean circulation was an important additional driver to the regional temperature variations (Giraudeau *et al*., 2010; Trommer *et al*., 2010; Yuan *et al*., 2018). Therefore, a better understanding of temperature and current circulation is needed to gain insights into the regional area, such as the Strait of Malacca and Andaman Sea.

The Strait of Malacca is a waterway that connects the Andaman Sea in the Indian Ocean to the South China Sea (SCS) (Thia-Eng *et al*., 2000; Amiruddin *et al*., 2011; Siswanto & Tanaka, 2014). It is located between the west coast of Peninsular Malaysia and the east coast of Sumatera, with a water depth of between 10 m and 200 m (Figure 1). The Andaman Sea occupies a significant position in the Indian Ocean, with a depth of more than 2000 m. The Strait of Malacca plays an important role as international shipping routes between the Indian Ocean and Pacific Ocean (Thia-Eng *et al*., 2000; Zubir, 2006; Mansor *et al*., 2016). The Strait of Malacca is funnel-shaped, and it is approximately 980-km long, varying in width from 52 km in the south to 445 km in the north. (Chen *et al*., 2014). The waters of the Strait of Malacca cover the area between 1.5°- 6 °N and 95°- 103 °E, while the Andaman Sea occupies the area between 6° - 13.5 °N and 92° - 99 °E.

The Strait of Malacca and Andaman Sea are influenced by tropical weather, particularly the Northeast and Southwest Monsoons (Wyrtki, 1961; Thia-Eng *et al*., 2000; Ibrahim & Yanagi, 2006; Amiruddin *et al*., 2011; Rizal *et al*., 2012; Liu *et al*., 2018). The Northeast Monsoon brings cool and dry air in December-January-February, causing a strong evaporation of surface water in the region (Chandran *et al*., 2018). The Southwest Monsoon is the warm and dry season, with weaker south-westerly winds that occur in June-July-August (Tangang *et al*., 2012). The wind direction varies according to the monsoon season, where the Northeast Monsoon winds are from the north to southwest, while the Southwest Monsoon winds move towards the northeast (Rizal *et al*., 2012). Monsoons also influence the SST of the Strait of Malacca and Andaman Sea. The region experiences warmer SST during the Southwest Monsoon and cooler SST during the Northeast Monsoon (Amiruddin *et al*., 2011; Chandran *et al*., 2018). The overcast skies and high precipitation lead to the lowering of sea temperature during the Northeast Monsoon (Varikoden *et al*., 2010; Roseli *et al*., 2014; Wong *et al*., 2016; Mahmud *et al*., 2018). Other than that, the changes of temperature in the Andaman Sea are also affected by the presence of inversions in the surface layers, intense surface evaporation and breaking of internal waves (Raju *et al*., 1981). However, this study focused only on the influences of monsoons on the SST variability in the Strait of Malacca and the Andaman Sea.

Generally, the Andaman Sea plays a significant role in the Strait of Malacca circulation, especially during the monsoon season (Wyrtki, 1961; Thia-Eng *et al*., 2000; Ibrahim & Yanagi, 2006; Rizal *et al*., 2012). Ibrahim and Yanagi (2006) state that there is an exchange of material and movement between the Andaman Sea and the SCS through the Strait of Malacca. There is an incoming of water from the SCS into the southern Strait of Malacca and towards the Andaman Sea during the Northeast Monsoon (Chandran *et al*., 2018). During the Southwest Monsoon, the Andaman Sea transports cool, deep, and saline water into the strait. In the Strait of Malacca, the surface flow is always directed north-westward towards the Andaman Sea, for both Southwest and Northeast Monsoons (Wyrtki., 1961; Thia-Eng *et al*., 2000; Rizal *et al*., 2012). This is because the sea surface elevation in the southern part is always higher than in the Andaman Sea during both monsoons (Thia-Eng *et al*., 2000; Rizal *et al*., 2012).

With the aim of improving knowledge on seasonal water characteristics and current circulation in the Strait of Malacca and Andaman Sea, attention should be devoted to conduct a research that uses approaches that are different than previous studies in the area. Thus, in this study, we explore how the seasonal monsoon cycle influences SST variations in the Strait of Malacca and Andaman Sea by using satellite-derived SST data retrieved from the Advanced Very High-Resolution Radiometer (AVHRR). We focused on the available satellite-derived SST data, which spans 33 years (January 1982 to December 2014). In addition, this study also introduces the possible seasonal thermal front between the Strait of Malacca and Andaman Sea through the calculation of the horizontal SST gradient. The surface currents from the model output, the Hybrid Coordinate Ocean Model (HYCOM), will be used to investigate the influence of monsoons on the ocean circulation of the Strait of Malacca and Andaman Sea. The understanding of long-term variability of SST of the Strait of Malacca and Andaman Sea from this study will provide vital information about the region, which was lacking.

Materials and Methods

This study is done on the Strait of Malacca and Andaman Sea using satellite-derived datasets and global ocean model HYCOM.

Study Area

This study covers the Strait of Malacca and Andaman Sea from 0°-13.5°N to 92°-102°E. The Strait of Malacca is shallow, with a steep slope of continental shelf at the northern side (~5°N) into the Andaman basin (Gibson *et al*., 2007). The southern exit for in-out flow of water from the basin is 3 km wide and 37 m deep (Kiran, 2017). The west coastal area of

Peninsular Malaysia and east coastal area of Sumatera are shallower, with a depth of around 30 m. The Strait of Malacca is protected from severe climate weather because the Sumatera Island in the west and the Peninsular Malaysia in the east serve as barriers (Wyrtki, 1961). The Strait of Malacca is broader in the northwestern region, with a width of about 341 km and a depth of around 66.4 m (Hii *et al*., 2006).

The Andaman Sea has a maximum depth of <4198 m, with an average depth of ~1096 m. The depth is approximately 200 m in the area around the islands and deeper than 2000 m in the centre of the Andaman Basin (Gibson *et al*., 2007). The western boundary at 12°N is marked by volcanic islands and sea mounts, such as the Andaman and Nicobar Islands. The eastern side of the Andaman Sea is shallow, with the continental shelf extending about 200 km off the coast of Myanmar and Thailand (Kiran 2017). Isobaths corresponding to 2000 m are shown in the figure below to illustrate the steepness of the basin near the islands and in the centre of the basin. To calculate the horizontal SST gradient, transects were drawn between the regions. The distance from transect A in the Strait of Malacca to transect B in the Andaman Sea is ~250 km.

Satellite-derived SST

Satellite remote sensing is one of the best methods to derive accurate ocean-wide SST data in daily to decadal periods. For climate studies, satellite remote sensing can be used to verify the variability of SST of the Strait of Malacca and Andaman Sea, where satellites can easily cover the region in high resolution and this can overcome the lack of data, which have not been provided by previous researches. There are few ways to collect data through satellites: multistage sensing, where data are collected from multiple altitudes; multispectral sensing, where data are collected in several spectral bands; or, multi temporal sensing, where data collection is carried out on more than one occasion (Devi *et al.,* 2015).

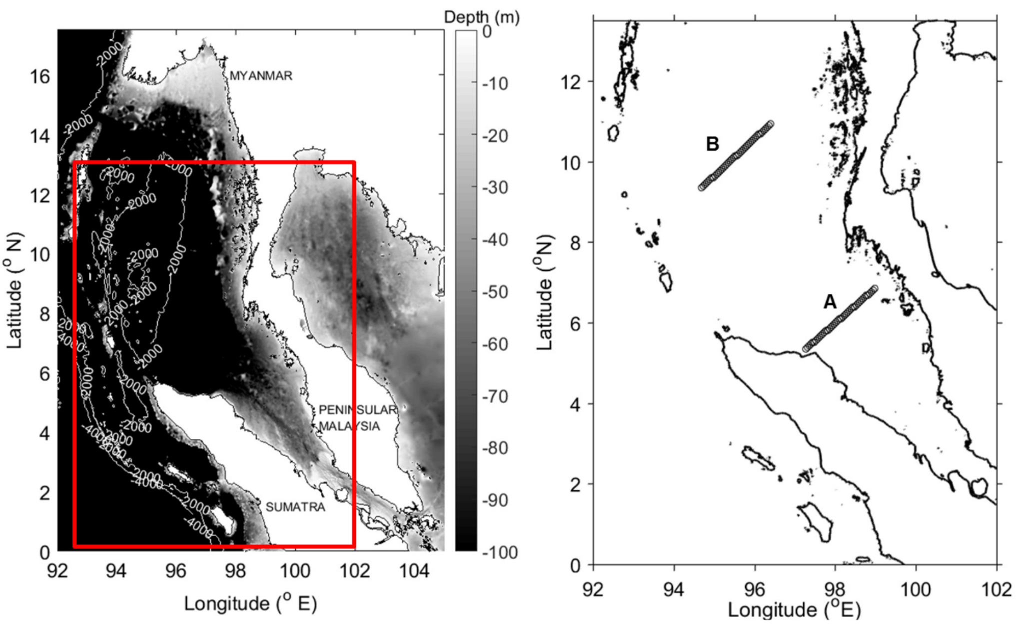

Figure 1: The map and bathymetry of the Strait of Malacca and Andaman Sea, with the depths given in metres. Isobaths of 2000 m and 4000 m are presented. The rectangle in the left panel represents the location of the study area. In the right panel, the asterisk points denote the distance of transects where the SST data were obtained. (A) The Strait of Malacca and (B) Andaman Sea. The bathymetry data are obtained from the GEBCO-gridded bathymetry data in the British Oceanographic Data Centre (BODC) database

The satellite-derived SST data used in this study was obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) on the AVHRR database (Saha *et al.,* 2018). The data are openly accessible on the NOAA website (https://www.nodc.noaa.gov/). The SST dataset is a collection of global data, covering the earth's surface twice a day (day and night), done by the NOAA, NCEI.

In this study, 33 years (1982–2014) of AVHRR Level-3 daily collated SST data (night-time) with a 4 km spatial resolution were applied to determine a comprehensive view of the SST variability in the Strait of Malacca and Andaman Sea. The SST daily data were averaged over the same months from May to August from 1982–2014 to represent the monthly SST climatology during the Southwest Monsoon. The mean average of SST was calculated to characterise the seasonal climatology in 2013.

The monthly means of the SST gradient are estimated by distance, defined as the transect A temperature minus the transect B temperature (Santos, *et al*., 2012; Kok *et al*., 2017);

$$\Delta DT = SST_{\text{(Transect A)}} - SST_{\text{(Transect B)}} \quad (1)$$

Where $SST_{\text{(Transect A)}}$ is in the northern Strait of Malacca (A) and $SST_{\text{(Transect B)}}$ in the middle of the Andaman Sea (B) (Figure 1). Therefore, a positive DT value indicates that the Strait of Malacca is warmer than the Andaman Sea, whereas a negative DT value indicates vice versa.

Sea Surface Currents from HYCOM

The sea surface current data (the u and v components of current) were retrieved from the global ocean model output, HYCOM global 1/12° analysis. The grid resolution is 0.08° longitude x 0.08° latitude with 41 vertical levels. HYCOM is a primitive equation ocean general circulation model that is based on the Miami Isopycnic-Coordinate Ocean Model (MICOM) (Bleck *et al.,* 1992). The data assimilation is based on the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005; Cummings & Smedstad, 2013). The initial state of the simulation is the in-situ and satellite SST, temperature and salinity profiles retrieved from ARGO floats, moored buoys and XBTs, as well as available satellite altimeter observations. The Naval Research Laboratory (NRL), Digital Bathymetric Data Base (DBDB2), was used for the bathymetry in HYCOM (Kok *et al.,* 2015). The HYCOM data can be retrieved from https://www.hycom.org/. The daily u and v components of velocity obtained from HYCOM was used to determine the seasonal current circulation of the Strait of Malacca and Andaman Sea. The daily u and v components and temperatures from the surface were averaged monthly, from November 2012 to December 2013.

Results and Discussion

The seasonal SST and sea surface currents variations in the Strait of Malacca and Andaman Sea were determined by using the satellite-derived data and global ocean model data.

Seasonal Variations of SST and Sea Surface Currents

Monthly analyses of the 33-year climatology data (1982-2014) surmised the seasonal variation in the Andaman Sea and Strait of Malacca (Figure 2). Cooler SST was detected in the Strait of Malacca and Andaman Sea during the Northeast Monsoon. Table 1 shows the SST during the Northeast Monsoon, ranging between 28.18°C and 28.97°C in the Strait of Malacca, and between 27.75°C and 28.09°C in the Andaman Sea. The SST started to warm (29.32-29.59°C) in the Andaman Sea and Strait of Malacca (29.35-29.81°C) during the first inter-monsoon season. During the Southwest Monsoon, the SST is the warmest in the Strait of Malacca (29.88°C ± 0.0146) and cooler in the Andaman Sea (27.99°C ± 0.0086). Hence, it formed a front between the Strait of Malacca and Andaman Sea. During the second inter-monsoon season, the SST decreased and was cooler in the Strait of Malacca (28.64-28.82°C) and warmer in the Andaman Sea (28.08-28.25°C).

Table 1: The minimum SST, maximum SST, mean SST and standard deviation SST based on the climatology SST for the Strait of Malacca and Andaman Sea

	MIN	MAX	MEAN	STD
Strait of Malacca				
DJF	28.18	28.97	28.51	0.0456
MAM	29.35	29.81	29.61	0.0171
JJA	29.56	30.12	29.88	0.0146
SON	28.64	28.82	28.74	0.0046
Andaman Sea				
	MIN	**MAX**	**MEAN**	**STD**
DJF	27.75	28.09	27.93	0.0058
MAM	29.32	29.59	29.48	0.0088
JJA	27.72	28.28	27.99	0.0086
SON	28.08	28.25	28.16	0.0035

The SST of the Strait of Malacca and Andaman Sea experience cooling events during the second inter-monsoon and the Northeast Monsoon seasons. During the second inter-monsoon season in October, the warm south-westerly winds weaken and the cold north-easterly winds blow over the region (Tangang *et al*., 2011; Akhir, 2012). During the Northeast Monsoon, when the north-easterly winds are stronger, the Strait of Malacca and the south eastern Andaman Sea experience heavy precipitation (Yanagi *et al*., 1997; Roseli *et al*., 2014; Wong *et al*., 2016; Mahmud *et al*., 2018).

The warmest SST of the Strait of Malacca and Andaman Sea was found during the first inter-monsoon season from March to May. During the Southwest Monsoon, starting from June until September, the warmer SST was found only in the Strait of Malacca. Drastic changes of the SST from the cooler Northeast Monsoon to the warmer inter-monsoon season are caused by the increase of shortwave radiation, the increase of sensible and latent heat fluxes, the weakening of surface winds and low amounts of total cloud cover, which consequently cause the ocean to warm from March and April (Yang & Wu, 2018; Ashin *et al*., 2019). The inter-monsoon period from March to April also plays an important role in increasing the thermal contrast between the neighbouring waters and causes the heating of the atmospheric column (Daryabor *et al*., 2015). The warming of the ocean continues until the Southwest Monsoon season due to the south westerly winds.

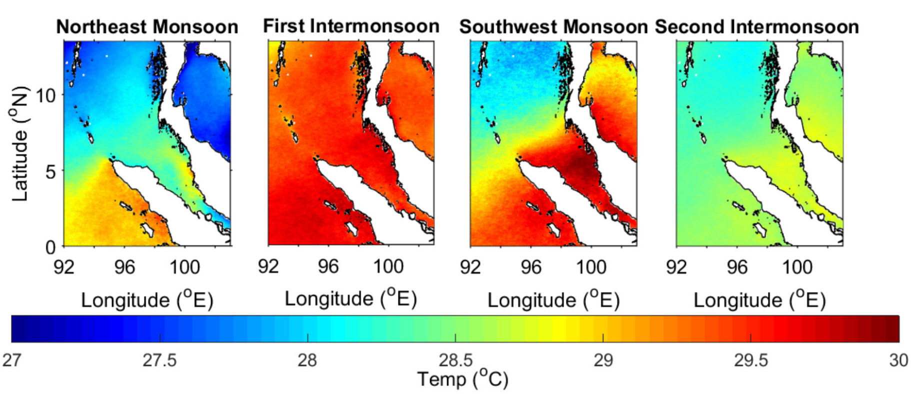

Figure 2: AVHRR's SST seasonal climatology from 1982-2014. The temperature ranged from 27°C to 30°C

The discussion afterwards will use HYCOM global ocean analysis data in 2013 to discuss the relationship between the SST and sea surface current circulation of the Strait of Malacca and Andaman Sea. The 2013 sea surface current is selected because that year is considered a normal year, as climate variability was absent.

During the Northeast Monsoon, the surface current can be clearly seen flowing north-westward from the northwest of Sumatera (~5°N) to the Bay of Bengal before splitting into two directions (Figure 3a). Part of the surface current from the coastal area of Sumatera flowed northward into the Andaman Sea. The surface current from the southern Strait of Malacca flowed northward along the west coast of Thailand into the Andaman Sea at a latitude of 8°N. At the northern region of the Andaman Sea, the surface current from the Bay of Bengal flowed southward before converging with the northward current at around 11°N and created a cyclonic eddy at ~12°N, 97°E. In the centre of the Andaman Sea, the current from the north flowed southward before converging with the northward current at the mouth of the strait at 7°N and turned back northward. In the Strait of Malacca, the northward current entered from the SCS into the Strait of Malacca because of the stronger flow of the surface current (Thia-Eng *et al*., 2000). As the Northeast Monsoon started to relax, the surface current circulation brought freshwater from the north Andaman Sea into the southern region, thus favouring a rapid SST increase. The incoming water from the SCS may also be the reason for the cooler water found in the southern Strait of Malacca during the Northeast Monsoon (Pang & Tkalich, 2003; Amiruddin *et al*., 2011). This cold water may enter from the SCS into the Strait of Malacca by the wind-driven current (Chen *et al*., 2014).

The surface current during the first inter-monsoon period is shown in Figure 3b. The northward surface current from the narrow strait flowed along the west coast of Peninsular Malaysia into the Andaman Sea at ~7-8°N. The surface current from the northern Andaman Sea flowed southward at 12°N. The current from the east of Sumatera flowed northward before converging with the southward current from the Andaman Sea and created a cyclonic eddy at the mouth of the strait at 7°N. Part of the surface current from the northern Andaman Sea flowed south-westward along the Andaman islands and out into the Bay of Bengal at 6°N. At ~10°N, the southward surface current converged and created a cyclonic eddy.

Figure 3c shows the surface current during the Southwest Monsoon. The strong flow surface current entered from the west of Andaman Sea at 10°N and flowed north-eastward. The surface current from northern Andaman Sea flowed southward before converging with the north-eastward current at 12°N and turned southward along the west coast of Thailand. Part of the surface current along the Andaman Sea islands created a cyclonic eddy at ~9°N. The surface current from the north of the Andaman Sea flowed south-westward out into the Bay of Bengal at the mouth of Sumatera (6°N). The current at the centre of the Andaman Sea flowed southward into the Strait of Malacca and later turned its direction to the coast of Sumatera.

During the second inter-monsoon period, the northward surface current from the Strait of Malacca flowed into the Andaman Sea along the west coast of Thailand at ~6°N (Figure 3d). The strong surface current entered from the northern Andaman Sea and flowed southward toward Sumatera at 12°N 96°E. Part of the surface current from the northern Andaman Sea flowed southward along the Andaman Sea islands before moving outward into the Bay of Bengal at 6°N.

Overall, the surface current flowed north-westward throughout the year from the southern Strait of Malacca toward the Andaman Sea due to the differences in the sea surface elevation between the two ends of the strait, with a downward slope toward the Andaman Sea (Wyrtki, 1961; Thia-Eng *et al*., 2000). This study agrees with Wyrtki (1961) and Marghany *et al*. (2003) as the surface current circulation was influenced by the monsoon wind. The findings of this study also agree with previous studies (Suwannathatsa *et al*., 2012; Chandran *et al*., 2018), where the current pattern in this region is induced by seasonal monsoons.

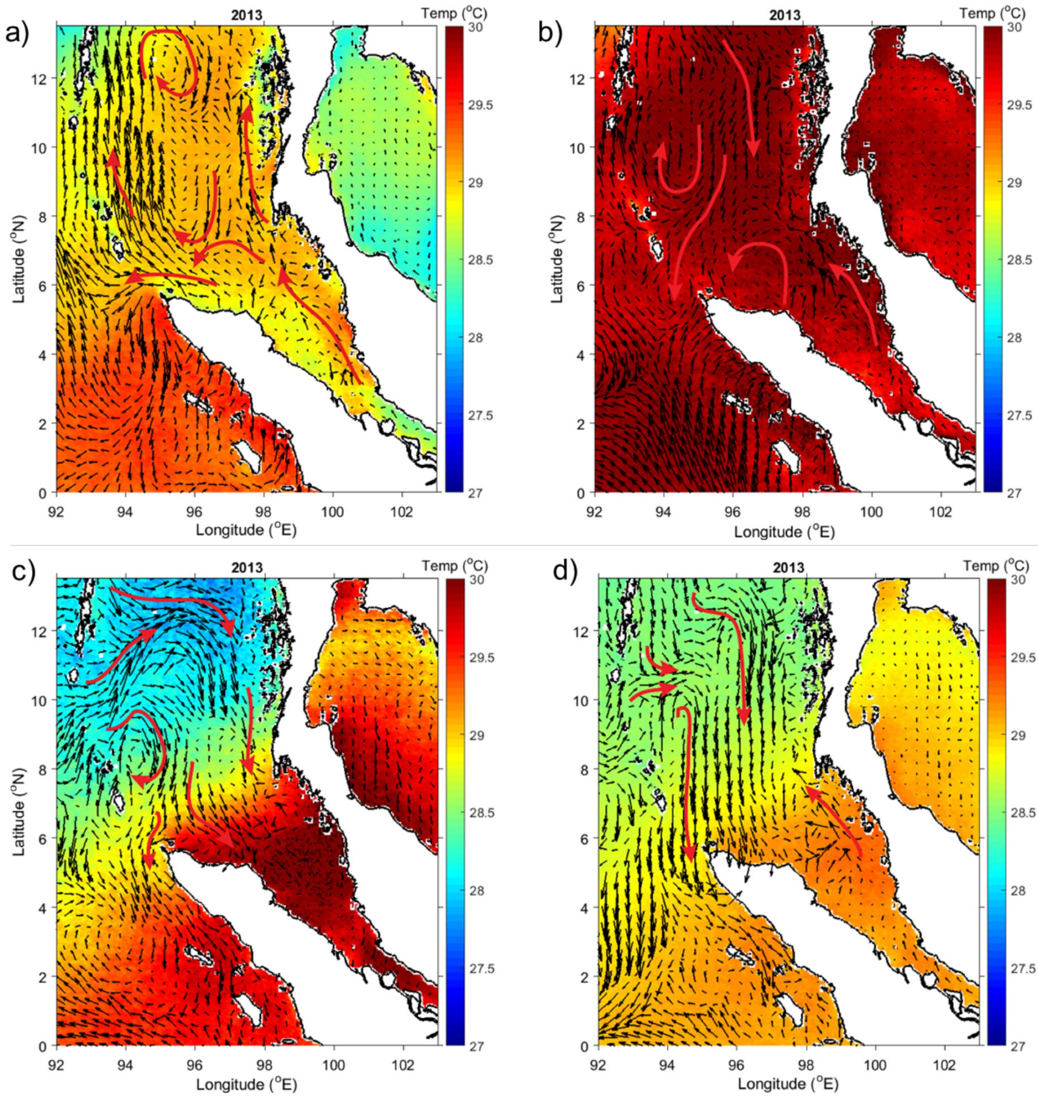

Figure 3: The seasonal climatology of surface current from HYCOM (unit: m/s) and AVHRR SST (shade in, unit:°C) in 2013 for (a) the Northeast Monsoon (b) The first inter-monsoon season (c) the Southwest Monsoon and (d) the second inter-monsoon season, 2013. The red arrows represent the current flow

Horizontal SST Gradient

The monthly temporal and spatial variations of the SST of the Southwest Monsoon in the Strait of Malacca and Andaman Sea from 1982 to 2014 are shown in Figure 4. Relatively warmer waters were observed in the Strait of Malacca from May to August, as seen from the climatology maps of the SST. The warmer waters were detected in the Andaman Sea in May and decreased from June to August.

Figure 4 shows that the SST is extremely warmer in May and reached up to 30°C in the Strait of Malacca and Andaman Sea. In June, the SST dropped to 28.5°C in the Andaman Sea, while the Strait of Malacca maintained the warmer SST of more than 30°C. In July and

August, the SST of the Andaman Sea continued to be cooler (27-28°C) than in the strait (29-30°C). Due to the strong horizontal temperature gradient, the thermal front is likely to be formed at the mouth of the strait (~6°N). It separated the cooler Andaman Sea from the warmer waters of the Strait of Malacca.

To clearly identify the interesting feature between the Strait of Malacca and Andaman Sea, the horizontal temperature gradient was calculated and presented in Figure 5. Based on the temperature gradient between the Andaman Sea and the northern Strait of Malacca, a high positive temperature gradient (+1.6°C) was observed from June to August at the northern Strait of Malacca. The positive temperature gradient indicates that the Strait of Malacca experiences warmer SST compared with the Andaman Sea. This might be due to the Indian Ocean, which experiences cooler temperature as the prevailing winds bring heavy precipitation to the region. Therefore, temperature was warmest in the strait and cooler in the Andaman Sea. There is a convergence flow that advects cold water from the cold region and warm water from the warm side during the monsoon season.

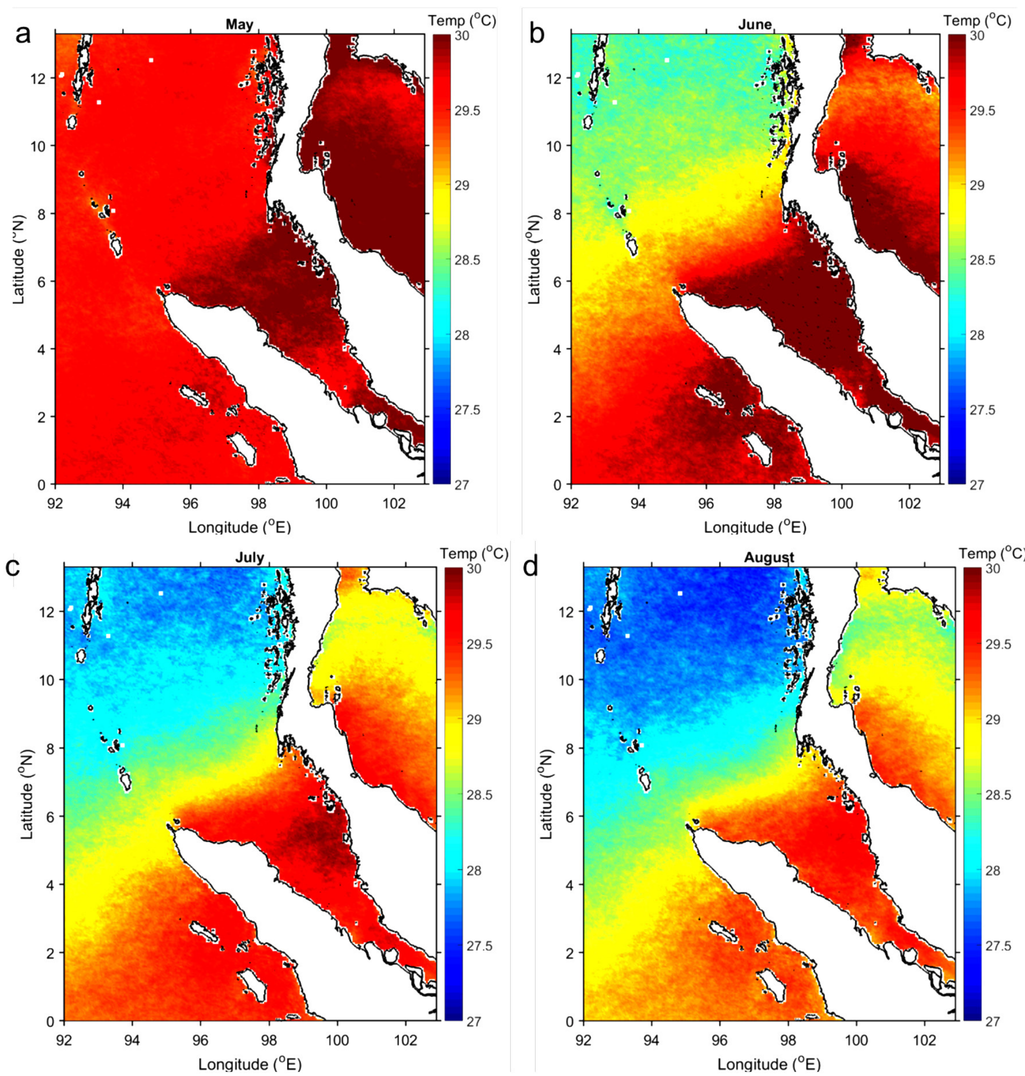

Figure 4: The monthly climatology of SST (unit:°C). (a) May, (b) June, (c) July and (d) August

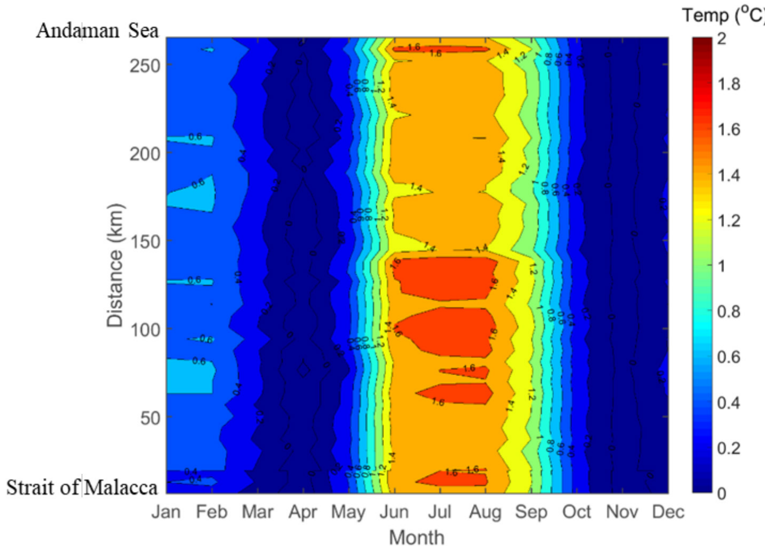

Figure 5: The monthly climatology of the horizontal SST gradient (unit:°C) from AVHRR (1982-2014). The distance is from transect A (Strait of Malacca) to transect B (Andaman Sea). The '0 km' distance represents transect A (Strait of Malacca) and above '250 km' represents transect B (Andaman Sea). The SST gradient was calculated by subtracting the SST value at transect A with the SST value at transect B ($\Delta DT = SST_{(Transect A)} - SST_{(Transect B)}$)

Conclusion

The SST and surface currents of the Strait of Malacca and the adjacent Andaman Sea varied seasonally due to the monsoons. The results show that the SST variability was characterised by the monsoon-driven current. In general, the currents of the Strait of Malacca flowed north-westward into the Andaman Sea every season. In the Strait of Malacca, the SST was cooler during the Northeast Monsoon, but started to warm during the first inter-monsoon period and continued until the Southwest Monsoon. This was different than the Andaman Sea, where the highest SST was found only during the first inter-monsoon period and the other season showed cooler SST. The horizontal SST gradient between the Strait of Malacca and Andaman Sea during the Southwest Monsoon is likely to cause the formation of a thermal front. As this region is lacking in fundamental information on physical properties, this study has been conducted to give an overview of the SST variability and surface currents of the Strait of Malacca and Andaman Sea. Interestingly, we have found the thermal front feature through the calculation of the horizontal SST gradient. As we did not discuss the front in detail, we hope this could spark future research regarding the dynamics related to the formation of the front. This study provided useful information on the Strait of Malacca and Andaman Sea that may be important for Malaysia's future climate and weather prediction.

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