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Thermal frontal zone along the east coast of Peninsular Malaysia

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ABSTRACT

Monthly satellite-derived sea surface temperature (SST) climatology was used to investigate the thermal frontal zone along the east coast of Peninsular Malaysia (ECPM) during both northeast and southwest monsoons. In addition, in situ hydrographic observations were conducted to investigate the vertical structure of thermohaline fronts during the southwest monsoon and inter-monsoon period. During the northeast monsoon, the locations of the front is determined by the speed of the southward flowing western boundary current, located near South Vietnam, which causes the tongue of cooler water, flooding into the ECPM. As the speed of southward flowing western boundary current increases, the cooler water tongue moves closer to the ECPM. On the other hand, as current speed decreases, the distinctive cooler water tongue recedes from the ECPM. During the southwest monsoon, the presence of a cooler water patch is observed in the SST climatology data and limited field data exhibit upwelling features (i.e. the presence of isotherm and isohaline shoaling towards the coast and surface). Analysis of European Centre for Medium-range Forecast (ECMWF) wind data show the presence of positive wind stress curl in the region, indicating a driving mechanism for upwelling. Additionally, analyses of onshore and offshore SST differences suggest that significant atmospheric forcing during different monsoon periods are responsible for the seasonal evolution of SST patterns.

1. Introduction

An ocean front can be defined as a region where there is a sharp horizontal contrast in the properties of seawater, such as differences in density, temperature, salinity or concentration of chlorophyll-*a* (Barth, 1989; Tong et al., 2010). Fronts are often observed in inland water, coastal zones and open ocean and can persist across a broad range of space and time (Brubaker and Simpson, 1999; Tong et al., 2010). One such area occurs in the southern South China Sea (SCS) near Peninsular Malaysia where a semi-permanent coastal front is observed through satellite images (Akhir et al., 2015). Although the study of atmospheric and oceanic processes is relatively new in the region, semi-annual monsoon changes and upwelling are believed to contribute to the frontal formation (Akhir and Kok 2014).

The east coast of Peninsular Malaysia (ECPM) is located in the southwest region of the southern SCS, within the shallow Sunda Shelf area (Fig. 1). The SCS is the largest semi-enclosed marginal sea in the western North Pacific Ocean and it is located between 0–25°N and 99–122°E. The SCS experiences strong seasonal variation that are typically associated with the northeast and southwest monsoon system (Dale, 1956; Wyrtki, 1961; Saadon and Camerlengo, 1996; Hu et al., 2000; Akhir and Yong, 2011). There is a northeasterly (southwesterly) wind over the SCS during the northeast (southwest) monsoon between November and March (May and September) (Morgan and Valencia, 1983; Chua, 1984). The periods of April and October are considered as the monsoon transition period, where winds are relatively calm and vary in direction (Morgan and Valencia, 1983; Taira et al., 1996). Previous studies showed that predominant northeast monsoonal winds drive a southward current that brings cooler and saltier water from the north of SCS. Conversely, the southwest monsoonal winds drive a northward boundary current that brings warmer and less saline water from the Karimata Strait (Akhir and Yong, 2011).

In the SCS, a strong southward flow of a western boundary current, which sometimes exceeds 0.5 m s^{-1}, develops near the south of Vietnam along the continental slope. This slope current advects cooler water southward, resulting in a formation of a cooler water tongue during winter. The development of the cooler water tongue formed a distinct horizontal temperature gradient between 103 and 104°E along the ECPM, which results in the

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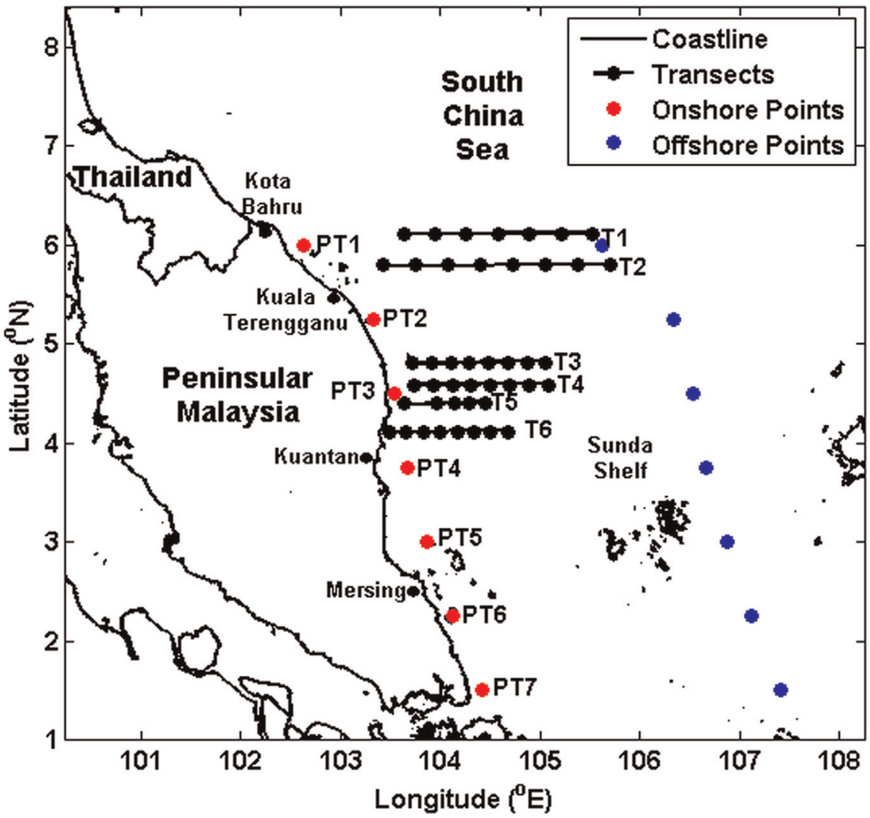

Fig. 1. Map of the Peninsular Malaysia. The black points with black lines represent the sampling transects (labelled as T1–T6). Red points (labelled PT1–PT6) and blue points represent the onshore and offshore points where the SST data were obtained. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

formation of a sea surface temperature (SST) front (Liu et al., 2004).

Numerous previous studies suggested that upwelling occurs along the ECPM during the southwest monsoon. Tong et al. (2005) used a hybrid method that combined ocean colour imaging with an Empirical Orthogonal Function (EOF) analysis to claim that the positive wind stress curl occurring along the ECPM is responsible for upwelling, similar to the mechanism that produces upwelling off the Vietnam coast slightly to the north. Recently, the modelling study by Daryabor et al. (2014) demonstrated that the southwest monsoon wind stress is responsible for inducing upwelling that produce elongated cooler SST (SST front) along the ECPM. In addition, biological studies also support the existence of a coastal upwelling feature in the area where a satellite-based fishery forecasting system for the ECPM predicted a productive fishing grounds near eastern Johor and off the coast of Pahang during the southwest monsoon (Mansor et al., 2001).

Previous studies relied primarily on seasonal time scales, which limits the understanding of the temporal evolution of the frontal formation. Thus, the monthly evolution of the front along the ECPM in the two monsoon seasons remains unclear. Furthermore, previous large scale regional studies of the SCS have not focused on the ECPM. To address these gaps, 14 years of monthly satellite-derived SST climatology, in conjunction with limited field measurements, are used for this study to observe the spatial and temporal evolution of the SST front along the ECPM. By examining the monthly climatological evolution of the SST patterns, differences in the frontal characteristics, and their associated forcing mechanism, are determined during the two monsoonal seasons. Furthermore, no study has yet investigated the *in situ* vertical structure of the thermohaline fronts in this shallow continental shelf area during the southwest monsoon where upwelling processes are shown to have a very strong influence on the thermohaline structures.

2. Methods

2.1. Satellite-derived SST

Satellite-derived SST data were obtained from the MODerate-resolution Imaging Spectrometers on-board the Terra spacecraft (MODIS-Terra). MODIS-Terra was launched in December 1999 to acquire multidisciplinary data in 36 spectral bands, covering the entire earth's surface within 1–2 days. The derived data included ocean colour, ocean productivity and SST. In the study, 14 years (2000–2013) of MODIS-Terra Level-3 monthly SST climatology, 4 μ band, night-time with 4 km spatial resolution were used to provide a synoptic view of the monthly SST frontal evolution along the ECPM. The data were assessed from the OceanColor (http://oceancolor.gsfc.nasa.gov/cms/).

2.2. Wind stress curl

A monthly wind speed vector climatology from years 2000–2013 was analysed to examine the relationship between the wind stress curl and the formation of the front. The wind data at 10 m, $0.75° \times 0.75°$ resolution, were first obtained from the European Centre for Medium-range Forecast (ECMWF) Interim Reanalysis (ERA-Interim) and further calculations were carried out to obtain the wind stress curl. The wind stress curl was calculated from meridional and zonal stresses using the formula adapted from Amedo and Villanoy (2003).

Wind stress curl is defined as: