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# Effects of Cardamom Mountains on the formation of the winter warm pool in the gulf of Thailand

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ABSTRACT

A small-scale winter warm pool covering an area of about 75,000 km$^2$ in the Gulf of Thailand (GoT) was uncovered using a suite of new high resolution satellite observations and historical in situ data. The core temperature of this warm pool is about 0.5–0.8 °C higher than that of the surroundings. The warm pool exists from the surface to the bottom of the sea. It forms in the first ten days of November, evolves to a mature stage from the mid-November to the early in January, and begins to decay in the mid-January. Our results show the formation of the warm pool is well correlated with the Cardamom Mountains on the Indo-China Peninsula. Due to the orographic effect of Cardamom Mountains, the low surface latent heat flux resulting from the wind wake leads to the formation of the warm pool in the sea. The interannual variability of the warm pool is affected by the El Niño-Southern Oscillation (ENSO) by modulating the strength of northeast monsoon each year. The warm pool has a possible implication for the marine ecosystem in the GoT.



## 1. Introduction

The Gulf of Thailand (GoT), located on the Asian continental shelf, is a semi-enclosed shallow sea surrounded by the Indo-China Peninsula and Malay Peninsula (Fig. 1). It connects with the South China Sea (SCS) on the east side of the Malay Peninsula. The GoT is approximately 720 km in length, with a maximum depth of 84 m. Over the Gulf, the northeast dry winds prevail in winter, causing little precipitation. While in summer, the southwest wet winds prevail, bringing plenteous rain. There has been a debate on the circulation pattern in the GoT: one point is that the circulation in the Gulf is mainly controlled by the monsoon, so the circulation is cyclonic in winter and anticyclonic in summer (Wyrtki, 1961). The other point is just reverse: the circulation is anticyclonic in winter and cyclonic in summer under the conjunct control of monsoon, bathymetry and SCS circulation (Sojisuporn et al., 2010).

Sea surface temperature (SST) is an important seawater attribute for studying the ocean dynamics, air-sea interaction, regional climate, and biological processes. SST in the GoT has been documented in previous studies (Wyrtki, 1961; Robinson, 1974; Siwapornanan and Humphries, 2011; Koad et al., 2012). SST in the GoT peaks in April and May, and reaches its minimum in January. Due to the strong solar radiation, the annual mean SST in the GoT is about 28.5 °C (Wyrtki, 1961). In winter, SST inside the GoT is higher than that in the Gulf mouth. This is mainly due to the cold water from the north advected by the SCS western boundary current (Tang et al., 2006). But the SST difference in summer is small between the Gulf interior and Gulf mouth (Standfield and Garrett, 1997). The interannual variability of SST in the Gulf is found to be consistent with the sea surface height (SSH) in the Gulf, and related with the El Niño (Siwapornanan and Humphries, 2011). On the interdecadal timescale, the trend of SST in the GoT is increasing with the speed of 0.003–0.089 °C/yr during the last 30 years (Koad et al., 2012).

The above analyses are the general understandings of the SST in the GoT. Due to the data resolution, the detailed SST pattern of the GoT has not been described completely and clearly in previous studies. Recently, we revisited the winter SST spacial distribution in the GoT using a new 9 km resolution climatology based on satellite observations, and found a small-scale warm pool (or warm patch) covering an area of about 75,000 km$^2$ surrounded by cold water in the GoT (Fig. 2). To our knowledge, this winter warm pool in the GoT has not been reported in the literature. This interesting phenomenon cannot be explained by the classical "bathymetric effect" theory (Xie et al., 2002): the deep water cools more slowly than that in the shallow water under the same surface cooling, thus SST in the middle of the GoT should be higher than that in the shallow coast. However, this is contradictory to the observational fact. This present study will firstly investigate the new SST feature and its evolution, then study the formation mechanism of the warm pool with a mixed layer

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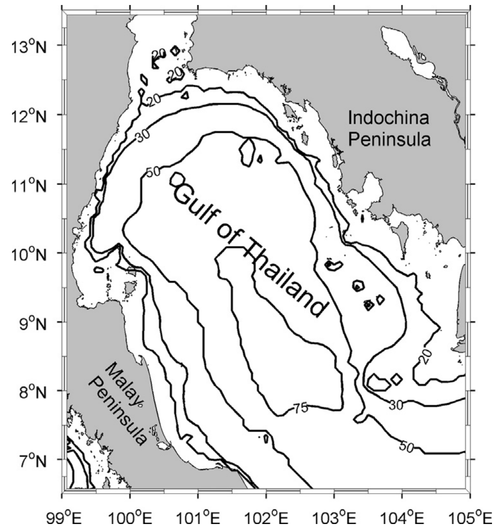


**Fig. 1.** Bottom topography of the Gulf of Thailand derived from the ETOPO5. The contours represent the 20 m, 30 m, 50 m and 75 m isobaths, respectively.

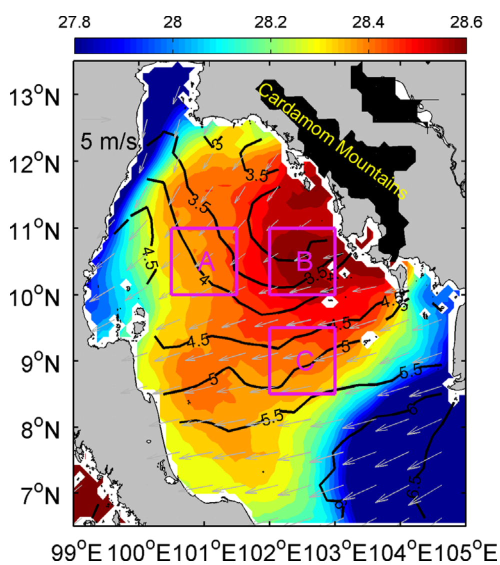


**Fig. 2.** Winter climatology of REMSS sea surface temperature (°C, color shading), averaged for November–January from 2006 to 2010, QuickSCAT surface wind vectors and wind speed (contours at 0.5 m/s intervals) averaged for November–January from 2000 to 2008. The Cardamom Mountains with elevations greater than 200 m are shaded in black.

model, next examine its correlation with El Niño-Southern Oscillation (ENSO), and finally explore its possible implication for the marine ecosystem in the GoT.

## 2. Data and model

### 2.1. Satellite data

Two satellite SST data sets are used: one is the Remote Sensing Systems (REMSS) SST product with 9 km resolution for the period from January 2006 to December 2010 (ftp://data.remss.com/SST/daily/mw_ir), and the other is National Climate Data Center (NCDC) SST data on a 0.25° grid from January 1982 to January 2011 (ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/). The REMSS SST is a merged SST product by both the infrared sensors from Moderate Resolution Imaging Spectroradiometer (MODIS), and microwave sensors from Advanced Microwave Scanning Radiometer for Earth Observing Mission (AMSR-E) and Tropical Rainfall Measuring Mission (TRMM) (Reynolds and Smith, 1994). The NCDC SST product is blended by the Advanced Very High Resolution Radiometer (AVHRR) and AMSR-E observations (the data is only from AVHRR before June 1, 2002).

Two satellite wind data are analyzed in this study: the daily Quick Scatterometer (QuikSCAT) wind data on a 0.25° grid from January 1, 2000 to December 31, 2008 (Hoffman and Leidner, 2005) (⟨http://podaac.jpl.nasa.gov/OceanWind/QuikSCAT/⟩), and the NCDC monthly wind data blended by the microwave radiometers on the Special Sensor Microwave Imager (SSMI), TRMM, AMSR-E and QuikSCAT (Zhang et al., 2006). This blended data is 0.25° resolution and available from January 1988 to December 2010 (⟨http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html⟩).

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite measures ocean color and chlorophyll a (Chl-a) concentration from October 1997 to December 2010. The data are obtained from the Distributed Active Archive Centre (DAAC), NASA (⟨http://oceancolor.gsfc.nasa.gov/⟩). Monthly gridded data on a 0.25° resolution are used in this study.

Heat fluxes are from two products: sensible heat and latent heat fluxes are from the Japanese Ocean Flux data set (⟨http://dtsv.scc.u-tokai.ac.jp/j-ofuro⟩) with Use of Remote Sensing Observations version 2 (J-OFURO2) (Tomita and Kubota, 2006); surface longwave radiation and shortwave radiation fluxes are from the Objectively Analyzed air-sea Fluxes (OAFlux, ⟨http://oaflux.whoi.edu/⟩) produced by the Woods Hole Oceanographic Institution (WHOI). The J-OFURO2 data is on a 0.25° grid, while the OAFlux product is on a 1.0° grid. Both datasets cover the period from January 2002 to December 2007.

Monthly climatologies are constructed for REMSS SST, QuickSCAT surface wind speed, SeaWiFS Chl-a, and surface heat flux for periods when these observations are available.

### 2.2. Hydrographical data

The monthly temperature and salinity climatology from U.S. Navy Generalized Digital Environment Model (GDEM-Version 3) is used here as the initial field of the model. GDEM data are on a 0.25° grid, which are derived from the temperature and salinity profiles in the Master Oceanographic Observational Data Set produced by the Naval Research Laboratory (Canes, 2009).

A hydrographic data set from World Ocean Database 2009 (WOD09) is used to verify our findings (⟨http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html⟩). It comes from a cruise (WOD Cruise Reference: TH001320) operated by Thailand from December 21, 1956 to January 10, 1957. Totally 54 CTD profiles shown in Fig. 3

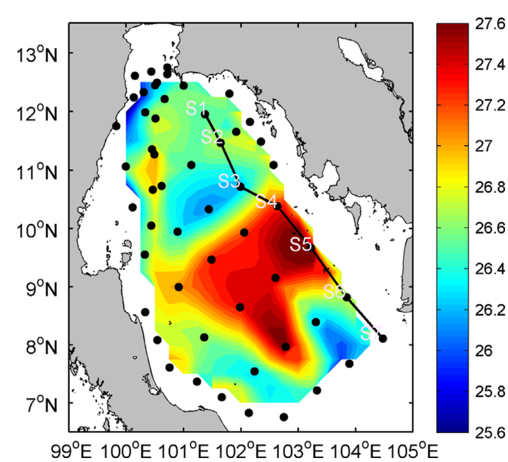


**Fig. 3.** Sea surface temperature (°C, color shading) derived from the WOD cruise TH001320 during the period from December 21, 1956 to January 10, 1957. Black dots are the observation stations. Black line is the transection for analyzing the vertical distribution of temperature.