Continental Shelf Research 29 (2009) 903–910

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Summertime sea surface temperature fronts associated with upwelling around the Taiwan Bank

Kuo-Wei Lan [a], Hiroshi Kawamura [b], Ming-An Lee [a,*], Yi Chang [a], Jui-Wen Chan [a,c], Cheng-Hsin Liao [a]

[a] Department of Environmental Biology and Fisheries Science, National Taiwan Ocean University, 2 Pei-Ning Road, Keelung 20224, Taiwan, ROC
[b] Ocean Environment Group, Center for Atmospheric and Ocean Studies, Graduate School of Science, Tohoku University. Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan
[c] Remote Sensing Laboratory, Taiwan Ocean Research Institute, Keelung 20224, Taiwan, ROC

ARTICLE INFO

Article history:
Received 11 April 2008
Received in revised form
17 December 2008
Accepted 27 January 2009
Available online 12 February 2009

Keywords:
SST front
Entropy-based edge detection
Upwelling
Chlorophyll-a
Taiwan Bank
Penghu Islands

ABSTRACT

It is well known that upwelling of subsurface water is dominant around the Taiwan Bank (TB) and the Penghu (PH) Islands in the southern Taiwan Strait in summertime. Sea surface temperature (SST) frontal features and related phenomena around the TB upwelling and the PH upwelling were investigated using long-term AVHRR (1996–2005) and SeaWiFS (1998–2005) data received at the station of National Taiwan Ocean University. SST and chlorophyll-a (Chl-a) images with a spatial resolution of 0.01° were generated and used for the monthly SST and Chl-a maps. SST fronts were extracted from each SST images and gradient magnitudes (GMs); the orientations were derived for the SST fronts. Monthly maps of cold fronts where the cooler SSTs were over a shallower bottom were produced from the orientation.

Areas with high GMs (0.1–0.2 °C/km) with characteristic shapes appeared at geographically fixed positions around the TB/PH upwelling region where SSTs were lower than the surrounding waters. The well-shaped high GMs corresponded to cold fronts. Two areas with high Chl-a were found around the TB and PH Islands. The southern border of the high-Chl-a area in the TB upwelling area was outlined by the high-GM area.

Shipboard measurements of snapshot vertical sections of temperature (T) and salinity (S) along the PH Channel showed a dome structure east of PH Islands, over which low SST and high GM in the maps of the corresponding month were present. Clear evidence of upwelling (vertically uniform distributions of T and S) was indicated at the TB edge in the T and S sections close to TB upwelling. This case of upwelling may be caused by bottom currents ascending the TB slope as pointed out by previous studies. The position of low SSTs in the monthly maps matched the upwelling area, and the high GMs corresponded to the area of eastern surface fronts in the T/S sections.

1. Introduction

The Taiwan Strait (TS), which connects the East China Sea with the South China Sea (SCS), is a narrow passage of 350 km in length with a maximum width of 180 km. It has complex bathymetric features (Fig. 1) including a shallow shelf (<50 m) along the Chinese coast, the Chang-Yuen Ridge (CYR, <50 m), Taiwan Bank (TB, <50 m) and Penghu Channel (PHC, <100 m). The PHC is located in the southeastern portion of the TS. To the southwest of the PH Islands is the TB (<50 m), which faces the northern part of SCS. In the TS, there are three major currents: (1) the Mainland China Coastal Current with low salinity, high turbidity and high nutrients, (2) the Kuroshio Branch Current with high temperatures, and (3) the South China Sea Warm Current (Jan et al., 2002).

Previous oceanographic studies clearly indicated the importance of upwelling and vertical mixing in the TS ecosystem (Hong et al., 1991). A strong seasonal variation in oceanographic conditions in this region was associated with both the dry winter northeasterly monsoon (November–February) and the wet summer southwesterly monsoon (May–August) (Kester and Fox, 1993). In summer, the surface current is predominantly wind-driven, and the bottom current flows upwards from the continental slope (Li and Liang, 1991). Hu et al. (2003), in a review of the previous studies on TS upwelling, mentioned that there were four major upwelling regions: (1) a region along the southwestern coast of the TS (SW upwelling), (2) a region along the northwestern coast of the TS (NW upwelling), (3) a region on the Taiwan Bank (TB upwelling), and (4) a region near the PH Islands (PH upwelling). Fig. 11 of Hu et al. (2003) showing satellite and in situ evidences of summertime upwelling is reproduced here as Fig. 2. The upwelling regions were also well identified by

* Corresponding author. Tel.: +886 2 24622192x5032; fax: +886 2 24634419.
E-mail addresses: aaman72422@msn.com (K.-W. Lan), kamu@ocean.caos.tohoku.ac.jp (H. Kawamura), malee@mail.ntou.edu.tw (M.-A. Lee), jeche7058@msn.com (Y. Chang), juwen2001@hotmail.com (J.-W. Chan), chliao@mail.ntou.edu.tw (C.-H. Liao).

0278-4343/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2009.01.015

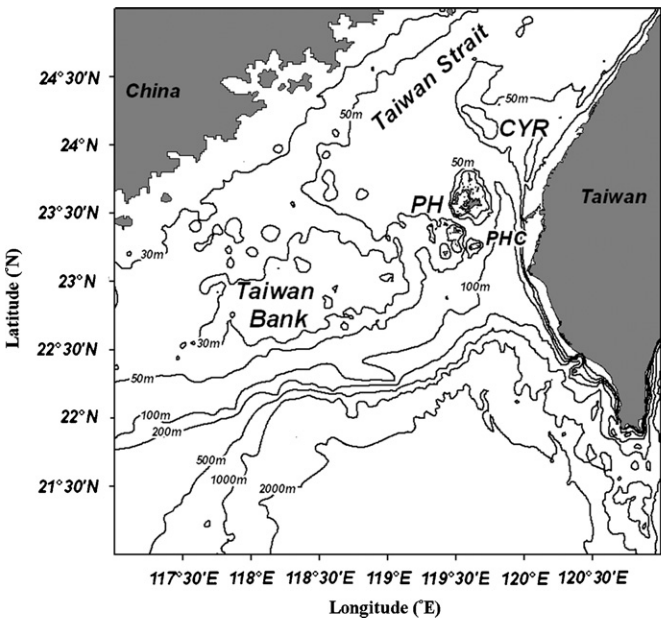

Fig. 1. Map of the study area with bottom topography and geographical names. Terrestrial areas are shaded and the contours indicate bottom depths in meters.

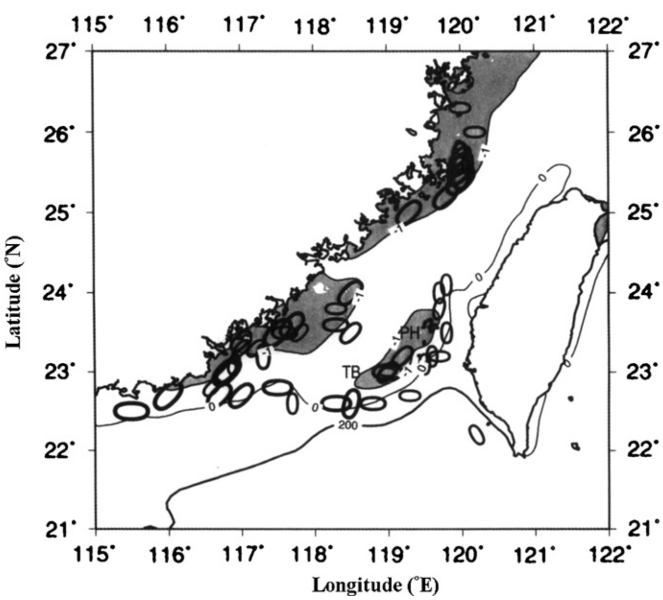

Fig. 2. Schematic locations of the summertime upwelling cores (ellipses) in the Taiwan Strait investigated by previous studies. The thin contour lines (with the low temperature zones shaded in light color) denote sea surface temperature (SST) contours derived from the summertime mean SSTs during 1996–1999. Here the spatial mean SST of 28.29 °C was subtracted from the mean SSTs to demonstrate the negative SST anomalies associated with the upwelling. The 200-m depth contour line is denoted as a thick line. Cited from Hu et al. (2003).

long-term satellite SST maps of summertime (Hu et al., 2001, 2003; Tang et al., 2004).

TB upwelling and PH upwelling occur year-round with varying strengths and scale (Hu et al., 2003). In the PH-upwelling region, the isotherms at 20-m layer showed the existence of a cold core with temperatures of 2–4 °C lower than those of the surrounding waters (Fan, 1979). The upwelling water of the PH-upwelling region was considered to be subsurface water ascending northward from the PHC. Tang et al. (2002) investigated upwelling in the TS with satellite-derived sea surface temperatures (SSTs). TB upwelling, showing a "banana" shape, positioned around the TB southern edge, has a size of about 2500–3000 km^2. The TB-upwelling region is characterized by SSTs lower than those of surrounding areas and chlorophyll-a (Chl-a) concentrations higher than those of surrounding areas.

Recently, high-resolution SST fronts have been developed to analyze oceanic features in coastal seas (e.g., Ullmann and Cornillon, 1999; Hickox et al., 2000; Shimada et al., 2005). The SST front information derived from the methodology of Shimada et al. (2005) and Chang et al. (2006) successfully identified synoptic oceanographic features of wintertime in the TS. They illustrated the four significant SST fronts: the Mainland China Coastal Front, the Peng-Chang Front, the Taiwan Bank Front and the Kuroshio Front. However, the technology of high-resolution SST fronts has not been applied to examine summertime upwelling in the TS where SST gradients (i.e., fronts) are enhanced (Hu et al., 2001; Tang et al., 2002).

The purpose of the present study was to investigate and describe summertime upwelling in the area around the TB and the PH Islands using high-resolution SST fronts together with the satellite SST and Chl-a data at a 1-km spatial resolution. Section 2 describes the data and methodologies used in the study. The results and discussions are given in Section 3 while Section 4 contains the summary and concluding remarks.

2. Data and methods

2.1. High-resolution satellite SST and Chl-a

We used NOAA AVHRR SST images with a grid size of 0.01° (Fig. 3a) produced by the A-HIGHERS system (Sakaida et al., 2000). The NOAA HRPT data including the AVHRR scenes were received at a ground station of National Ocean Taiwan University (NTOU) (Lee et al., 2003). The accuracy of the retrieved SST data was about 0.6 °C in the seas around Taiwan (Lee et al., 2005). We used high-resolution satellite Chl-a images with a 0.01° spatial resolution. Using the SEADAS (NASA, O-Reilly et al., 1998), the satellite Chl-a images (Fig. 3c) were processed from the Sea-viewing Wide Field-of-View Scanner (SeaWiFS) data locally received at NTOU. All the received scenes of HRPT and SeaWiFS for summers (June–September) of 1996–2005 were processed for this study. Then, monthly mean maps with a 0.01° spatial resolution were calculated (e.g., Figs. 5 and 7).

2.2. Methodology of SST front detection

For SST front detection, we adopted an entropy-based edge detection method developed by Shimada et al. (2005). The methodology was independent of seasonally/regionally varying geophysical parameters, and could detect and retain finer-scale SST fronts (Fig. 3b). Its effectiveness was verified by Chang et al. (2006), who used it to detect wintertime SST fronts in the TS.

We used monthly maps of frontal SST gradient magnitude (GM) and orientation. In terms of the SST front positions detected by the entropy-based method, the GM is defined as follows:

$$\mathrm{GM} = \sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2} \quad (^\circ\mathrm{C/km}) \tag{1}$$

where T is SST, and x and y axes are respectively directed towards the east and north. The GM was computed for all frontal pixels for each image, and averaged for a monthly composite (Shimada et al., 2005). The GM composite maps reveal statistical appearances of the SST front which are related to dynamic features of TB frontal systems. Values of the GM are also important for describing frontal characteristics.