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Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements

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Abstract

The Taiwan Strait is located at the confluence of the East China Sea and the South China Sea in the west Pacific Ocean. Several upwelling zones in the Taiwan Strait are noted for their high fisheries production; these upwelling zones have been studied in the past decade, but we have no overall picture on the size and temporal changes of these upwelling zones due to only limited in situ observation over short periods of time. The present paper investigates upwelling in the Taiwan Strait with satellite remote sensing data of NOAA-derived Sea Surface Temperature (SST) and SeaWiFS-derived Chlorophyll-*a* (Chl-*a*) and shipboard measurements during summer 1998. Results reveal five upwelling zones: (1) coastal upwelling near Pingtan Island (PTU), (2) coastal upwelling between Meizhou and Xiaman (MXU), (3) big coastal upwelling near Dongshan Island (DSU), sometimes extending to offshore, (4) small occasional upwelling near the Penghu Island (PHU) and (5) an intensive upwelling in the Taiwan Bank (TBU). TBU was extensively studied over summer 1998. Results showed that the TBU looks like a banana in shape in the southern edge of the Taiwan Bank; it intensifies in its southeastern edge. The size of TBU was about 2500–3000 km^2, with a mean value of 2796 km^2. The temperature difference between the upwelling and non-upwelling areas was about 2.5–3.5 °C for early August with a mean value of 2.3 °C on July to October. Series of images indicated a short-term variation of TBU and showed that high Chl-*a* concentrations (up to 0.8–2 mg m^{-3}) zones coincided with low SST (25–26 °C) zones in terms of location, time, and shape. These upwelling zones change with size and intensity center from time to time. Field measurements of water temperature, salinity, and Chl-*a* in 1998 are consistent with satellite measurements.

1. Introduction

The Taiwan Strait, between Taiwan Island and Mainland China, provides a link between the East China Sea and the South China Sea (SCS), and plays a very important role in water exchange between these two seas. Several upwelling zones in the Taiwan Strait have been identified as a result of hydrological, chemical, and biological observations (Hong, Qiu, Ruan, & Hong, 1991; Li, 1993), such as the Taiwan Bank Upwelling (TBU), which is the most important fishing ground in the Taiwan Strait. However, we have very limited knowledge on the spatial and temporal variations of those upwelling areas in the Taiwan Strait due to limited in situ observations. In the present study, we describe the application of satellite-derived sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) to investigate upwelling in the Taiwan Strait. We particularly emphasize the spatial and temporal variations of SST and pigment concentration (PC) in the Taiwan Bank Upwelling (TBU) during summer monsoon.

Upwelling areas occupy only 0.1% of the world ocean, but their fisheries production almost equals that of the whole coastal continental shelves in the world (Zhen, 1991). In other words, fisheries production in upwelling areas accounts for almost 50% of the world total fisheries production (Ryther, 1969). Therefore, a good understanding of upwelling processes and characteristics is very important for fish production and management. Oceanographic research

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has clearly indicated the importance of coastal upwelling and vertical mixing in the Taiwan Strait (Hong et al., 1991). A strong seasonal variation exists in this region, associated with both the dry northeast winter monsoon (November–February) and the wet southwest summer monsoon (May–August) (Hong et al., 1991; Kester & Fox, 1993). Tang and Liu (1996) reported a seasonal reversal of surface currents on the western side of the strait with the Cold China Coastal Current (CCCC) during winter and the South China Sea Warm Current (SCSWC) during summer. In summer, the surface current has the predominant property of wind-driven current, and the bottom current flows upwards from the continental slope (Li & Liang, 1991). Also, there are occasional injections of the Kuroshio water into the eastern side of the strait (Chen & Shen, 1999). Although many research cruises were conducted in the past decade for a biogeochemical study of upwelling in the Taiwan Strait (Hong et al., 1991; Huang, Xu, & Li, 1997; Wang & Chern, 1992), no overall picture is available on spatial and temporal changes of upwelling in this area due to limited in situ observations that were performed only over short periods of time. Fisheries managers and oceanographers would like to know: How many upwelling locations exist in the Taiwan Strait? What are the spatial distributions of these upwellings? What is the temporal variation of TBU? What is the temperature difference between upwelling and non-upwelling areas?

Satellite remote sensing may help to answer these questions since the technologies can monitor a large region for a long period. While examining satellite Nimbus' Coastal Zoon Color Scanner (CZCS) ocean color images along the Chinese coastal areas during 1978 to 1986, Tang and Ni (1996) and Tang, Ni, Müller-Karger, and Liu (1998) noticed high Chl-*a* in some specific areas in the Taiwan Strait and suggested that this could be related to upwelling. Advanced Very High Resolution Radiometer (AVHRR) SST data have been applied for water temperature study in Daya Bay located in the southwestern part of the Taiwan Strait (Tang, Kester, Wang, & Lian, 2000). The present study utilizes satellite data and in situ measurements to investigate SST and Chl-*a* in the Taiwan Strait with the following objec-

(a)

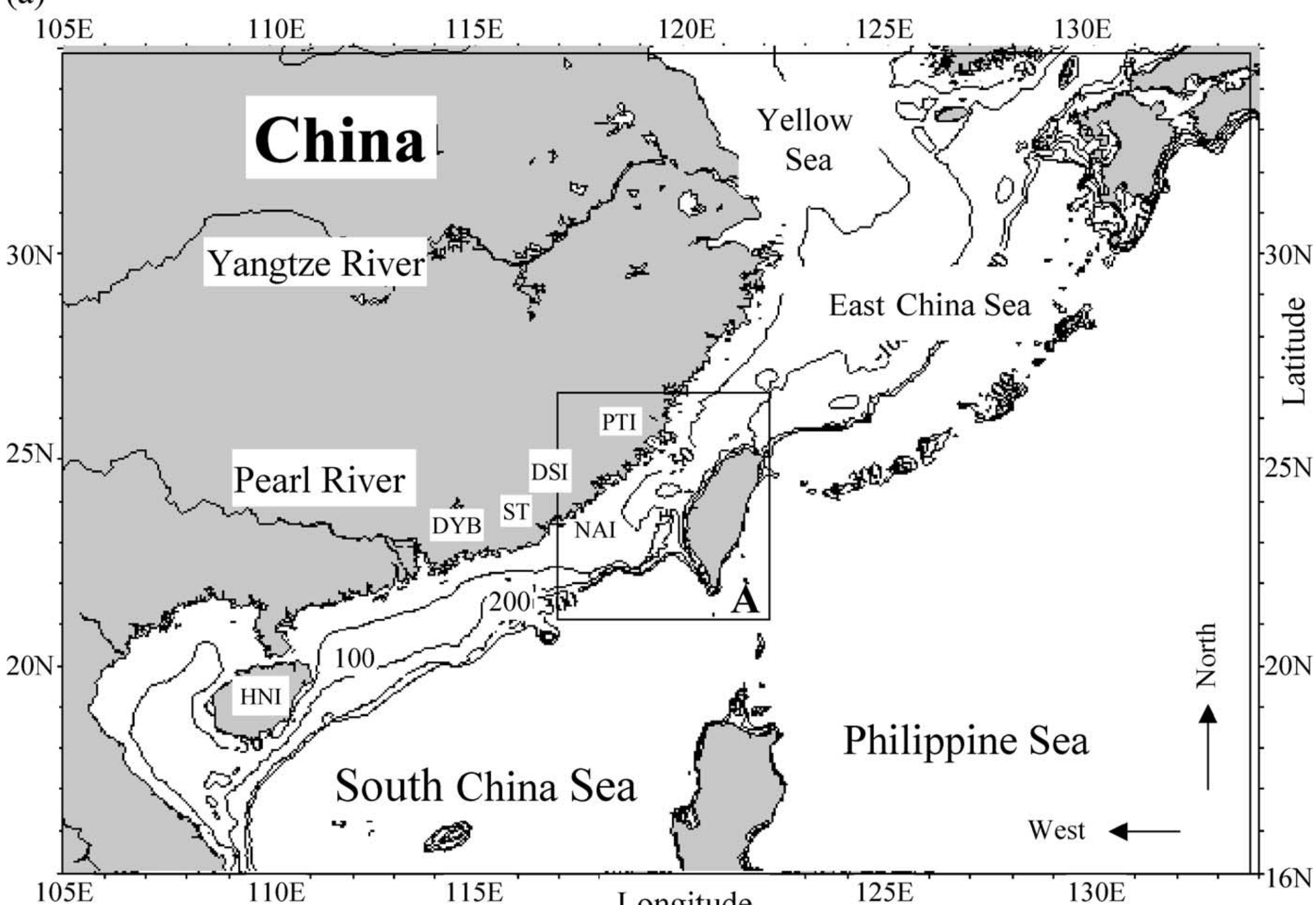
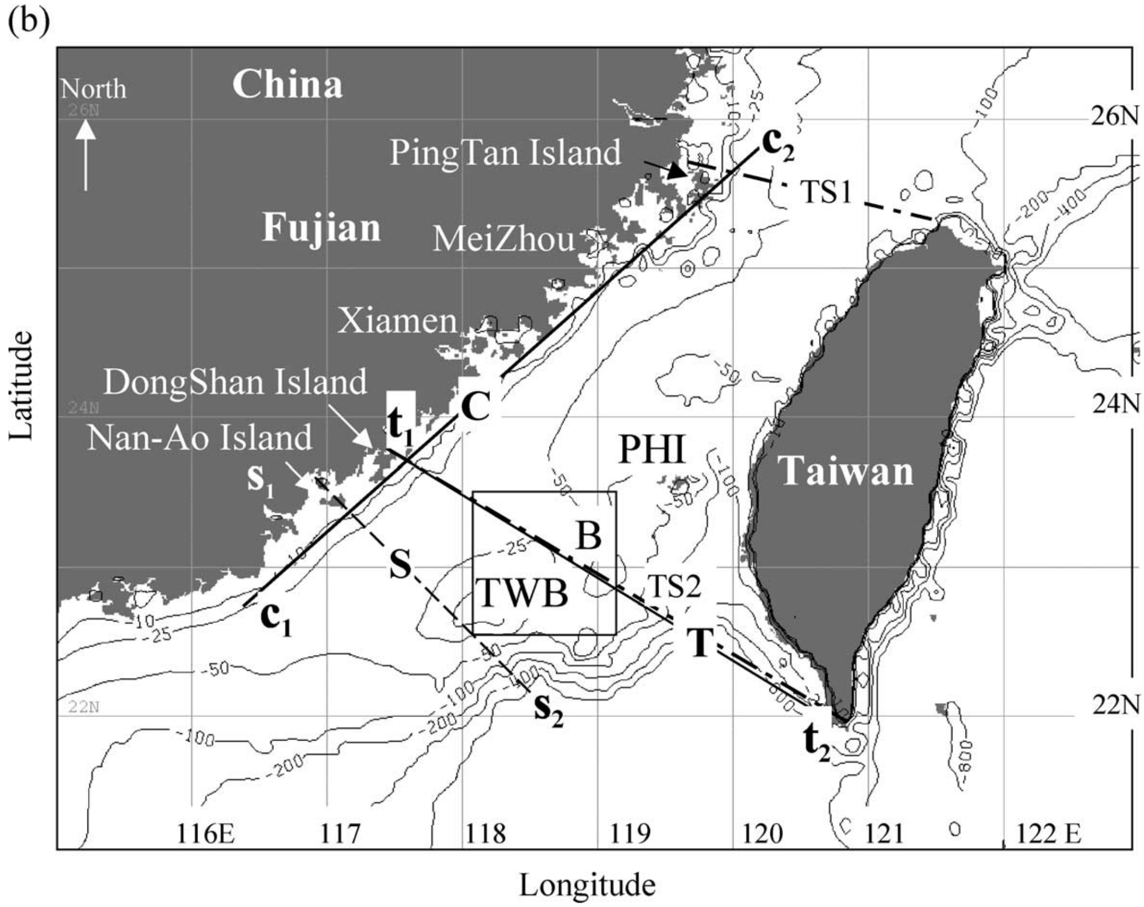


Fig. 1. (a) Location of the study area (box) in the Taiwan Strait. PTI: Pingtan Island; DSI: Dongshan Island; NAI: Nan-Ao Island; ST: Shantou; DYB: Daya Bay; HNI: Hainan Island Fig. 1. (b) The bathymetric chart of Taiwan Strait showing water depth (m). Box B: Satellite AVHRR SST data sampling box. Transect S: Data sampling transect of shipboard measurement. Transect C and T: Data sampling transect of satellite AVHRR SST; TWB: Taiwan Bank. The lines TS1 and TS2 indicate the limits of the Taiwan Strait.



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tives: (1) effectiveness of using satellite sensors to detect upwelling in the Taiwan Strait; (2) determination of spatial variations of upwelling during the summer season; and (3) examination of progressive temporal variations of upwellings and their characteristics. The results may contribute to a better understanding of the dynamic process of upwelling in the Taiwan Strait, and could provide a sound scientific basis for fisheries management.

2. Methods

2.1. Study area and shipboard measurements

The study area is shown in Fig. 1a (box A) and Fig. 1b. The Taiwan Strait (between the two broken lines TS1 and TS2 in Fig. 1b) is situated between Taiwan and Mainland China, at the confluence of the East China Sea and the South China Sea in the west Pacific Ocean. However, researchers on Taiwan Strait generally cover the domain of 116.5–121.5°E and 22–26°N. It is 50–70 m deep over much of its extent, with a shoal area of 15–20 m in the Taiwan Bank (TWB) (23°N, 118–119°E) in the southern region (Fig. 1b). The TWB is known as a famous fishing ground. The Penghu Islands (PHI) is located in the center of the Taiwan Strait (Fig. 1b). Moreover, there is Pingtan Island (PTI) in the northwest and Dongshan Island (DSI) in the southwest part of the Taiwan Strait. Meizhou (MZ) and Xiamen (XM) are in between PTI and DSI (Figs. 1b and 2a).

Xiamen University and Fujian Institute of Oceanology of China conducted a comprehensive survey in the Taiwan Strait in August 10–16, 1998. The SBE21 Thermosalinograph (with additional WETStar miniature chlorophyll fluorometer attached) was used in this survey. During the underway measurement, the seawater was pumped up and the sea surface temperature, sea surface salinity, and chlorophyll-*a* were measured by the respective sensor with the sampling time of 30 s, while the longitude and latitude were positioned by the GPS. Salinity was measured by Sea-Bird conductivity sensor. Therefore, the underway measurements provided useful information about water temperature, salinity, chlorophyll-*a*, and primary productivity in the Taiwan Strait. Underway measurements performed on August 12 along transect S (s_1: 23.2956°N, 117.2848°E to s_2: 22.1952°N, 118.4093°E) (S in Fig. 1b) from northwest (s_1) near the Nan-Ao Island (Fig. 1b) southeastward (s_2) were analyzed. We have a total of 1339 data points of the shipboard measurements along transect S. Unfortunately, transect S of the research cruise did not fully cross TBU.

2.2. Sea surface temperature from NOAA's AVHRR

NOAA normally maintains two operational polar orbiting satellites that provide SST from the AVHRR instruments. SST images of 1 km spatial resolution were obtained from the satellite receiving station of the Hong Kong University of Science and Technology (Tang et al., 2000). AVHRR images were processed to obtain SST using the TerraScan software. Following the geo-coordinate mapping of the images, the application of the TerraScan SST algorithm, and the regional sectioning into a 1000×680 pixels array. The pathfinder AVHRR SST (Kilpatrick, Podestá, & Evans, 2001) were processed through the Mutichannel (MCSST) algorithm version 4. Coefficients of the MCSST algorithm were calculated over a 5-month period and centered over each month by a least-square fit to SST buoys (Vazquez, Perry, & Kilpatrick, 1998). Global statistical measure of the MCSST data relative to drifting buoys show consistent biases (buoy minus satellite) and root mean square error of -0.1 and 0.5–0.7 °C, respectively (McClain, Pichel, & Walton, 1985). All AVHRR SST images covering the period of July 1 to October 30, 1998 on the study area were processed and checked. There are about two to five images per day but sometimes there is no image because of cloudy conditions. Coastal areas are sometimes cloudy, which disturbs the satellite SST measurements. However, through careful visual checking, we found a series of valuable SST images that allowed us to display the short-term variation of TBU and DSU in August 1998.

A small box (box B in Fig. 1b) covering the TBU area is set to investigate a time series of presence and extent of the upwelling area. For comparing SST difference between Taiwan Bank Upwelling (TBU) and no upwelling areas, we investigated 186 available scenes of NOAA AVHRR images collected between July 1 and September 30, 1998, and we sampled 46 suitable images for examining the time series of TBU. All pixels in Box B were extracted for SST values in the Taiwan Strait. The area of the TBU was estimated by examining the water temperature difference

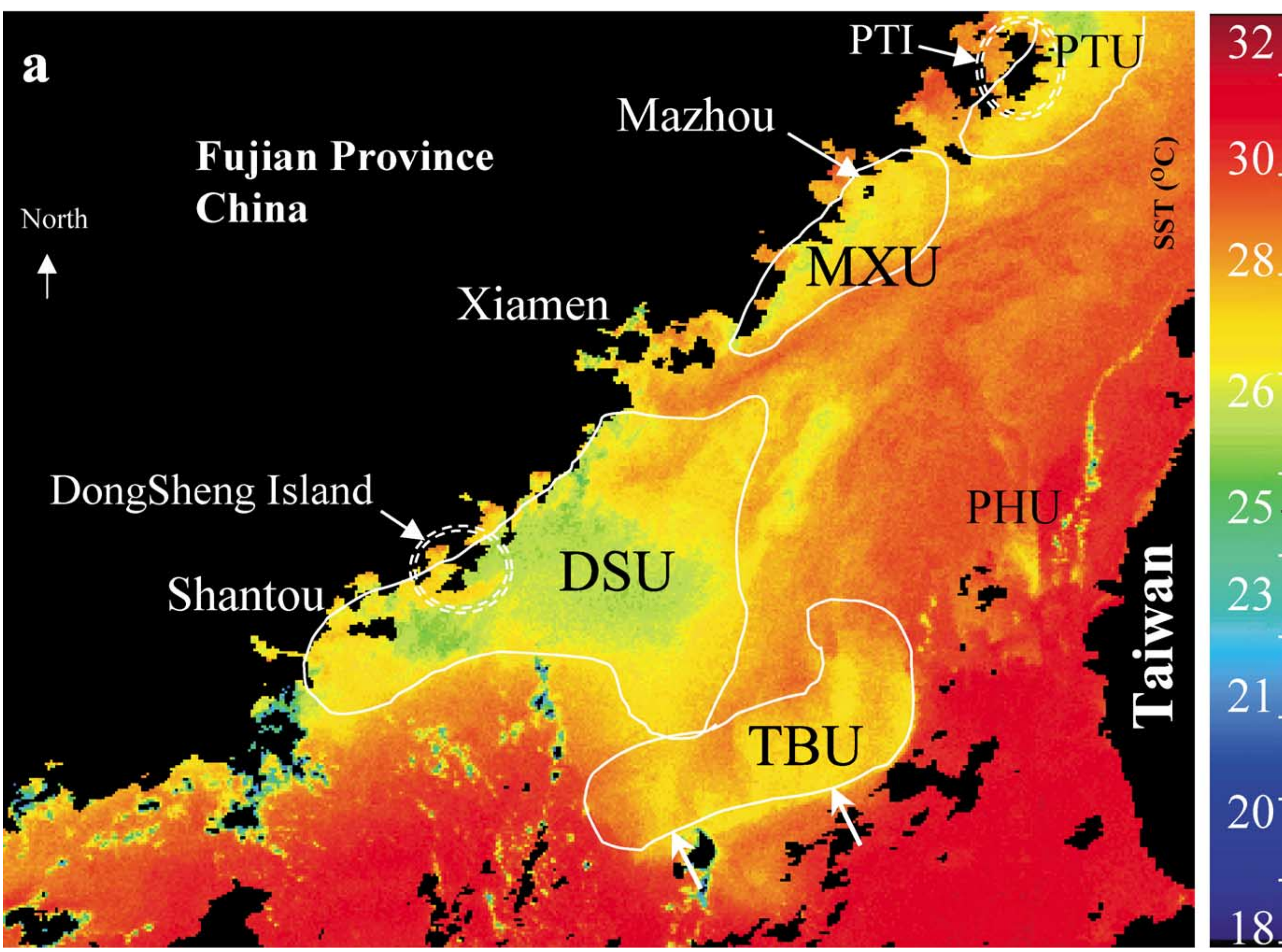
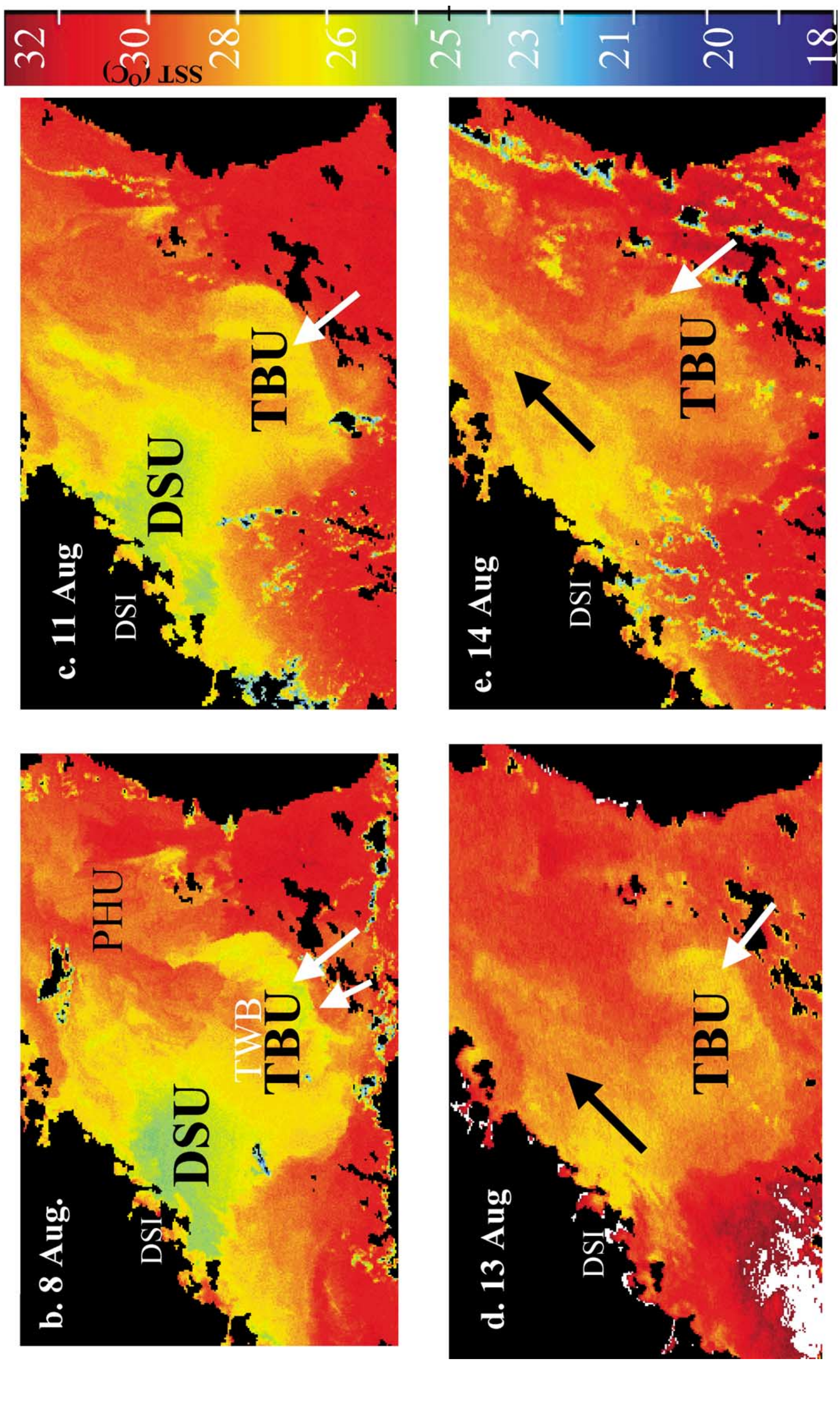


Fig. 2. (a) SST distributions in the Taiwan Strait on August 11, 1998. Lands and cloudy areas are shown in black color. There were several areas with distinctly low SST: PTU, PHU, MXU, DSU, and TBU. (b–h) SST images showing short-term variation of Dongshan Upwelling (DSU) and Taiwan Bank Upwelling (TBU) in August 1998. Lands and cloudy areas are marked in black color. Color bar indicates water temperature. Areas with white pixels are > 32 °C which is beyond the range of the color bar.



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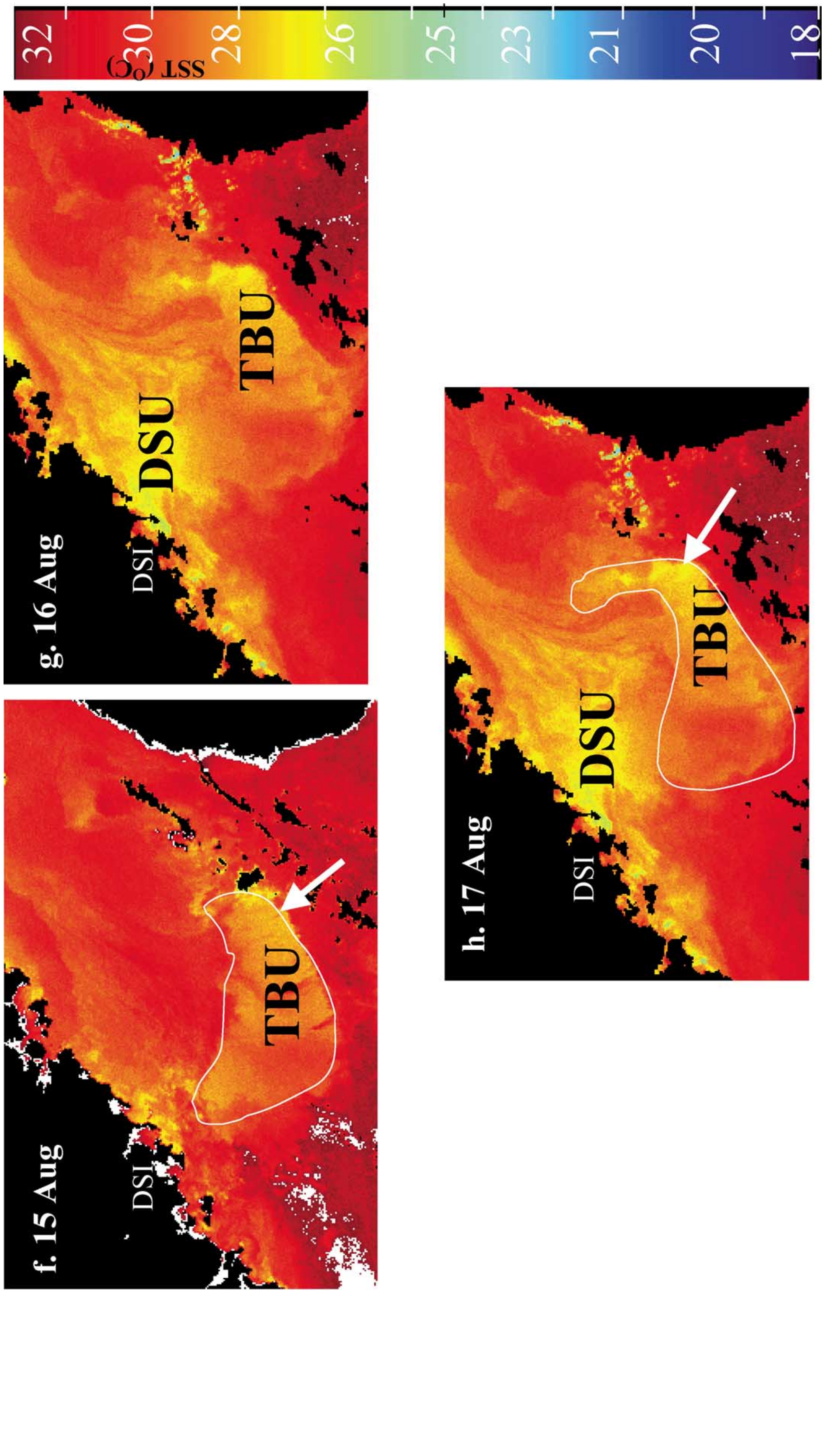


Fig. 2 (*continued*).

between the upwelling and the non-upwelling areas by using WIM software (Kahru, 1999; Tang et al., 2000). The upwelling waters were defined by a change in SST values (1–3.0 °C) on the images. Every pixel was accounted as 1 km^2.

Two other transects (T and C) were selected for determining water temperature changes in these areas. Transect T (T in Fig. 1b) crosses the Taiwan Strait from northwest (t_1) to southeast (t_2) crossing the TBU. Transect C (C in Fig. 1b) is parallel to the Fujian coast from southwest (c_1) to northeast (c_2). NOAA AVHRR derived SST along these two transects on August 7, 1998 have been examined. We have 278 SST measurements along transect T (Fig. 1b) crossing TBU, and 445 SST measurements along transect C (in Fig. 1b).

2.3. Chlorophyll concentration retrieved from satellite images

The SeaStar satellite with SeaWiFS was launched in late 1997. It repeats the same orbit every 16 days (233 orbits) and covers the same point on the earth every 1–2 days depending on the latitude (Yoder, McClain, Feldman, & Esaias, 1993). SeaWiFS data are particularly useful for determining Chl-*a* levels. We used the SeaWiFS data archived and distributed by NASDA/EORC. It is done as an ADEOS-I/OCTS project through the cooperation with NASA. The SeaWiFS data received at the Kumamoto station of the Tokai University is transferred to NASDA/EORC. The SeaWiFS Chl-*a* products are processed by SEADAS with the standard atmospheric correction and OC4 algorithm. The SeaWiFS images of 1 km spatial resolution of local coverage were processed through SEADAS within the frame of Asian I-Lac Project in Tohoku University, Japan (Tang & Kawamura, 2001; Tang, Kawamura, & Luis, 2002). After investigating all available SeaWiFS data obtained in August 1998, we are able to select a time series of Chl-*a* images in the study area, which mach SST images with the same time period.

3. Results

3.1. Low SST zones in the Taiwan Strait

SST distribution in the Taiwan Strait on August 11, 1998 is shown in Fig. 2a. Generally, SST is high (about 30 °C) in the northern part of the South China Sea, including the Taiwan Strait. However, several distinct areas of particularly low SST can be easily observed: (1) Pingtan Upwelling (PTU), in the coastal area near Pingtan Island (PTI) in the northwestern of the Taiwan Strait; (2) Meizhou–Xiaman Upwelling (MXU), in the coastal area between Meizhou and Xiaman; (3) Dongshan Upwelling (DSU), in the coast upwelling near Dongshan Island (DSI), which is the largest and strongest one close to the Fujian coast; (4) Taiwan Bank Upwelling (TBU), a low SST area with a banana shape (arrows in TBU) located in the southeast of the Taiwan Bank (TWB); (5) Penhu Upwelling (PHU), an occasional small area of low SST near the Penghu Island (PHI, in Fig. 1b).

3.2. Short-term variation of sea surface temperature (SST)

A time series of SST images (Fig. 2b–h) illustrate the short-term variation of TBU and DSU between August 8

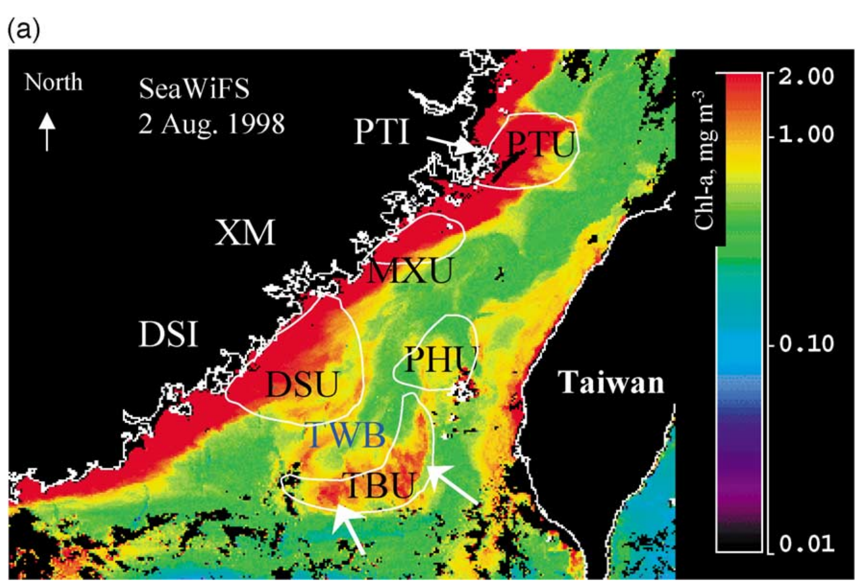
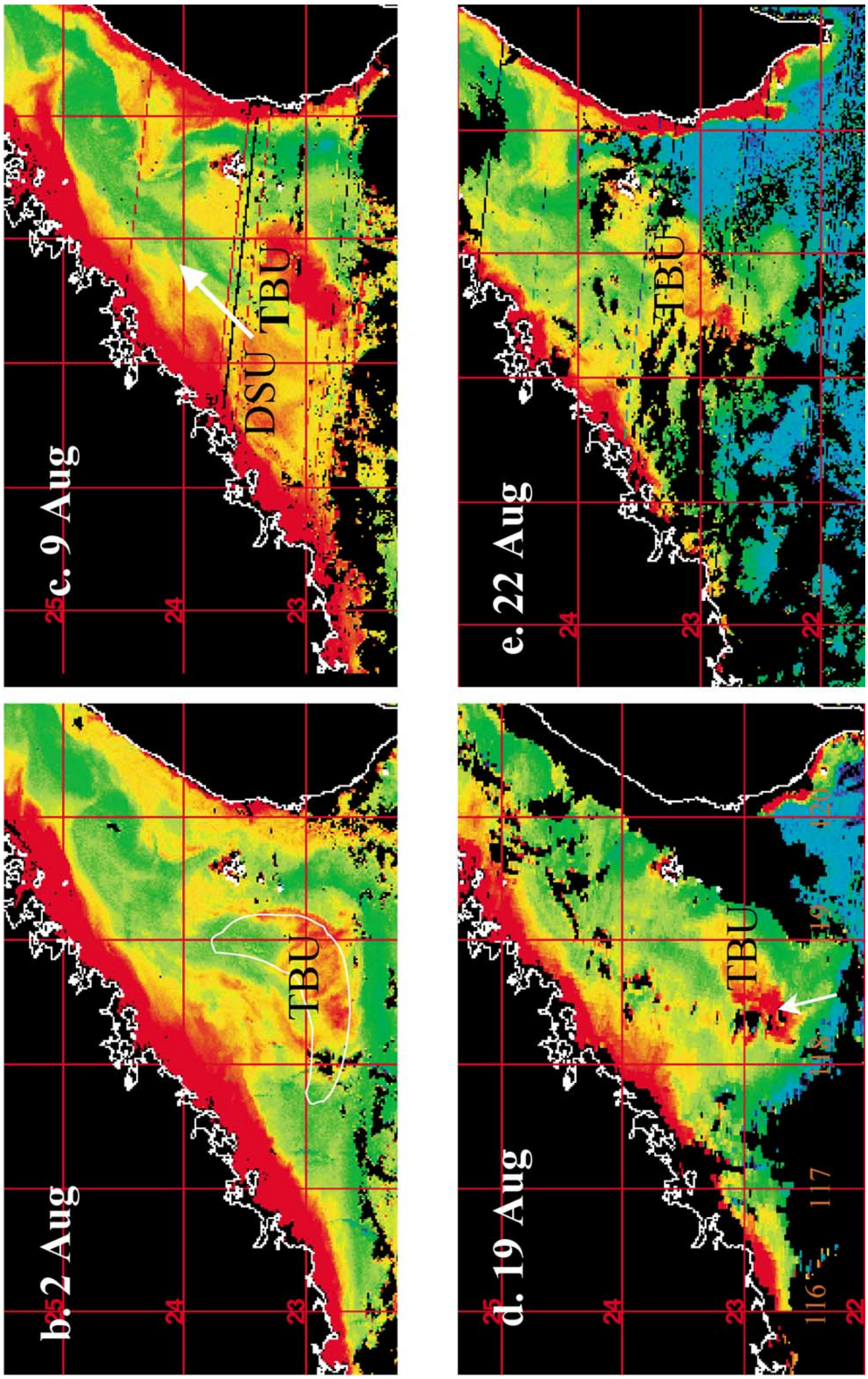


Fig. 3. (a) SeaWiFS image on August 2, 1998 showing high chlorophyll concentrations in upwelling areas of PTU, MXU, DSU, TBU, and PTU. (b–g) SeaWiFS images showing a short-term variation of Chl-*a* on TBU in August 1998.



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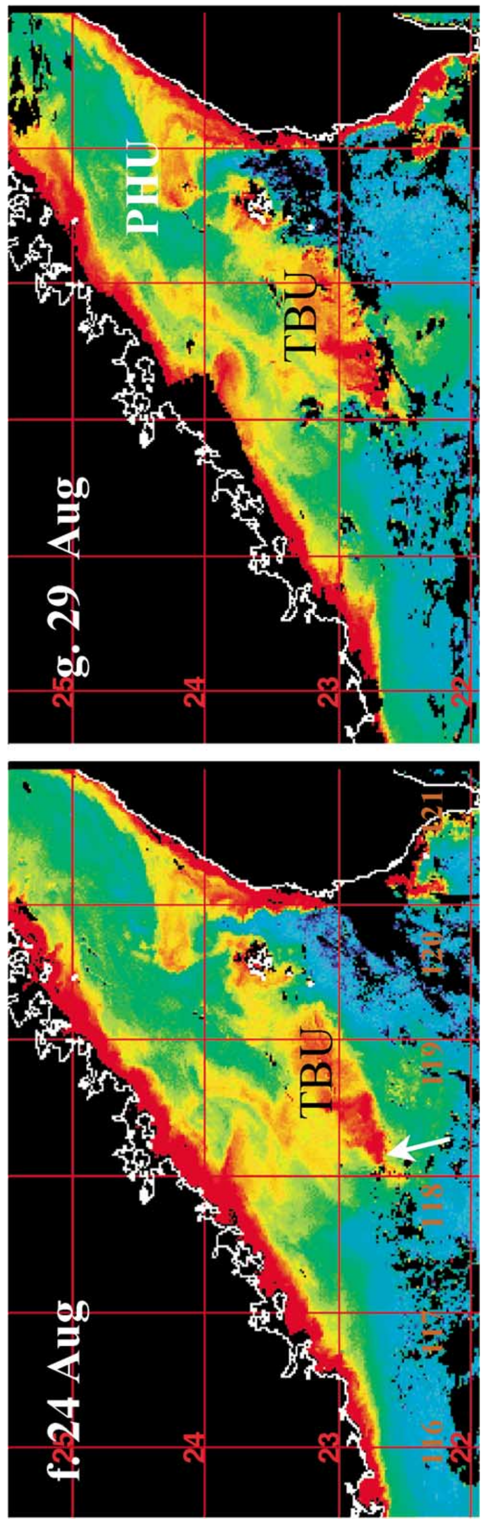

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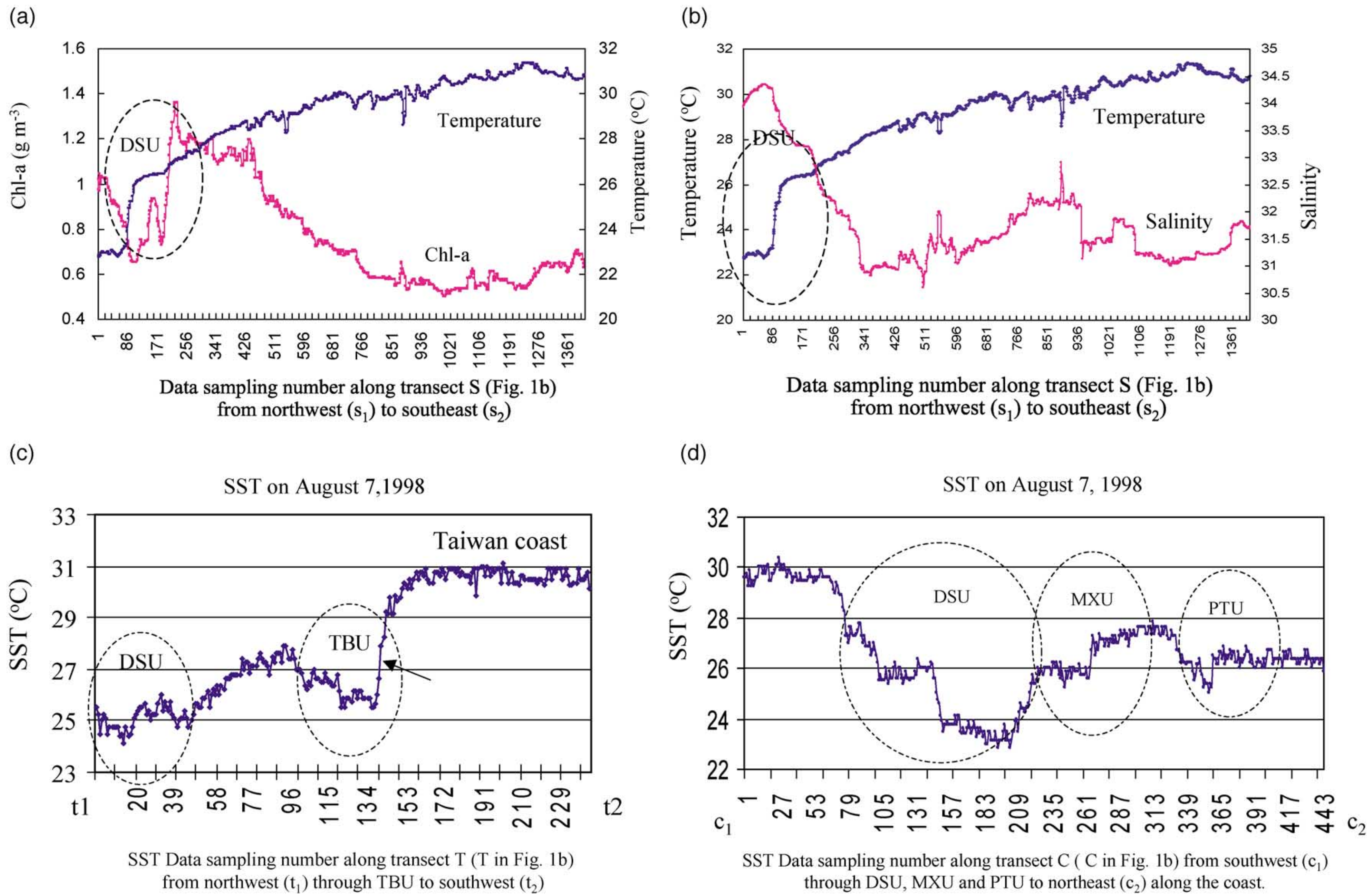

Fig. 4. Water temperature, Chl-*a* and salinity through the TBU in the Taiwan Strait. (a) Shipboard measurements of temperature and Chl-*a* of along transect S (S in Fig. 1b) from s_1 (near the Nan-Ao Island) southeastward to s_2 on August 12, 1998. The *X*-axis indicates sampling number of the shipboard measurements. (b) Shipboard measurements of water temperature and salinity along transect S (S in Fig. 1b) from s_1 to s_2 on August 12, 1998. The *X*-axis indicates sampling number of the shipboard measurements. (c) NOAA AVHRR derived SST along the transect T (T in Fig. 1b) on August 7, 1998. The *X*-axis indicates the number of pixels from northwest (t_1) through the TBU to the south end of the Taiwan Island (t_2). SST is about 25 °C in DSU, 25–26 °C in TBU, 30–31 °C in the other places. There is a very sharp of SST change of 4.5 °C between TBU and Taiwan coastal waters. (d) NOAA AVHRR derived SST along the transect C (C in Fig. 1b) on August 7, 1998. The *X*-axis indicates the number of pixels from c_1 through the DSU, MXU, and PTU to c_2. SST is about 30 °C in north of South China Sea, but much lower (24–25 °C) in DSU. Low SST also appeared in MXU and PTU.

and 17, 1998. There are areas in Fig. 2 that are white in color. This is because SST is higher than 32 °C and, therefore, is out of the region of the color bar.

On August 8 (Fig. 2b), SST in the Taiwan Strait is generally about 30 °C in the north of South China Sea and in the Taiwan Strait. The low SST (about 24 °C) in DSU area has a large extent (about 3000–3500 km^2) in a round shape; TBU is in the southern Taiwan Bank located southeast of DSU. It is smaller (about 2000 km^2), and with a banana shape. The fronts are clearly displayed at the east edge of the TBU (arrows in Fig. 2b). The largest gradient of SST (25–31 °C) is in the south of the Taiwan Bank (TWB). It is confirmed again later by shipboard data and SST data in Figs. 4 and 5. On August 11, DSU and TBU are still present but they are getting weaker, especially TBU. On August 13 and 14, TBU continues weakening, with a shape modification shifting slightly northward (see arrows in Fig. 2c–e). DSU merged with TBU and gets very weak on August 15 (Fig. 2f). The TBU become significantly larger and spread to the west with sharp edges. The lowest SSTs are observed along the southwest of Taiwan Bank (arrow). On August 16 and 17 (Fig. 2g,h), DSU gets stronger again.

3.3. Distribution and short-term variation of Chl-a

Distribution pattern of SeaWiFS-derived Chl-*a* concentrations in the Taiwan Strait on August 2, 1998 is shown in Fig. 3a. High Chl-*a* concentrations (1–2.0 mg m^{-3}) appear along the Fujian coast, which can be observed in three zones as what shown in Fig. 2: (1) PTU; (2) MXU; (3) DSU in the coastal area near Dongsheng Island (DSI). These three upwellings are within waters very close to land, so artifacts in the satellite-retrieved Chl-*a* signal within these near shore ‘‘upwelling’’ area may be present due to nonpigment particulate material. Other two zones are off the coast, they are: (4) TBU, the intensive upwelling with high Chl-*a* concentrations (1–2.0 mg m^{-3}) along the southeast edge of the TWB (two arrows in Fig. 3a). The high Chl-*a* centers (two arrows in Fig. 3a) merge as a banana shape. It is similar with SST images (Fig. 2a); and (5) PHU, which is small and occasionally appears between the Fujian coast and the Taiwan Island in the southern Taiwan Strait. Five white circles in Fig. 3a indicate the locations of low SST upwelling regions on the Chl-*a* image.

After a careful examination, we found a series of good SeaWiFS images (Fig. 3b–g) displaying short-term variation of Chl-*a* on TBU in August 1998. TBU is displayed in a banana shape by high Chl-*a* concentration on August 2 (Fig. 3b). On August 9 (Fig. 3c), both of TBU and DSU become stronger, and there is a tendency of moving northeastward (arrow in Fig. 3c), which was already highlighted by the SST pattern of August 11 and 14 (Fig. 2c,d). From August 19 on, TBU gets intensive in the southwest center (arrow in Fig. 3d), DSU gets weakened; PHU appears on August 24 and 29 (Fig. 3f,g).

3.4. Temperature, Chl-a, and salinity change between upwelling and non-upwelling areas

Fig. 4a,b displays shipboard measurements of water temperature, Chl-*a* concentrations, and salinity on August 12, 1998. Low temperature (22–26 °C), high Chl-*a* (0.8–1.2 mg m^{-3}), and high salinity (26–30) in the coastal upwelling area (DSU) were measured in the west side of the transect S (S in Fig. 1b).

Satellite AVHRR SST vary along the transect T and C (T and C in Fig. 2a) on August 7, 1998 (Fig. 4c,d). We have 278 SST measurements along the transect T (Fig. 4c) crossing TBU. SSTs is high (30–31 °C) in the Taiwan coast, but reach only about 24–25 °C in DSU and about 25–26 °C in TBU. There is a large SST gradient (arrow) of 5 °C (from 26 to 31 °C) between TBU and the Taiwan coastal waters (arrow in Fig. 4c). Transect C (C in Fig. 2a) is along the Fujian coast from southwest through the DSU, MXU, and PTU to northwest. We have 445 SST measurements along the transect C. SST in northern South China Sea is about 30 °C, but is lower (24–25 °C) in DSU (Fig. 4d). Low SST zones also appear in MXU and PTU.

The size of TBU area ranges from 400 to 4000 km^2 during the study period (Fig. 5a), and the mean value is

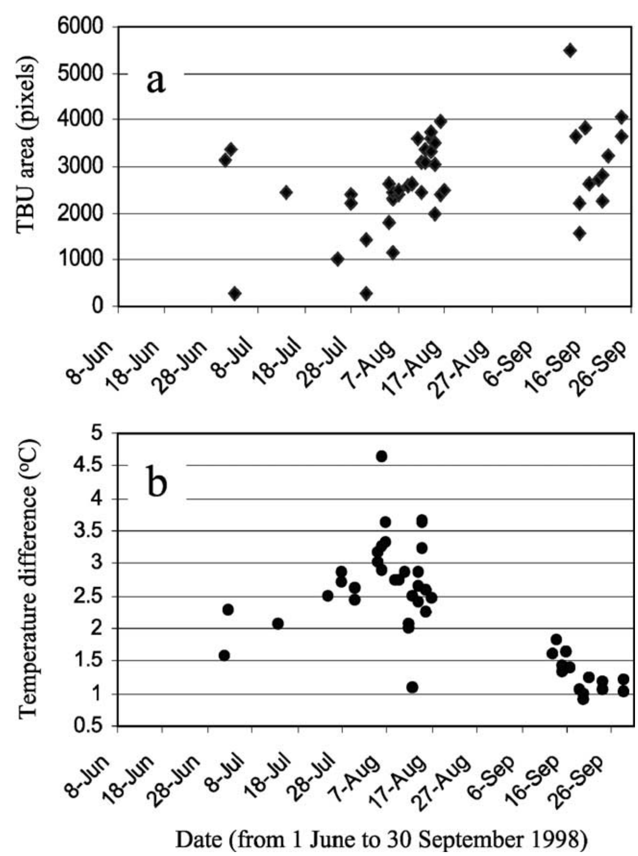

Fig. 5. The SST time series analysis on TBU from July 1 to September 30, 1998. (a) Time sires of TBU upwelling area. Mean value of the TBU is 2795.8 (pixels) km^2. (b) Temperature difference between the upwelling area and non-upwelling area. Mean temperature difference is 2.35 °C.

2796 km^2. The temperature (SST) difference between upwelling and non-upwelling is about 2.5–3.5 °C in early August, and about 1.0–2.0 °C in September (Fig. 5b). The mean value of SST difference is 2.33 °C.

In summary, five distinct zones featuring both low SST and high Chl-*a* concentrations have been identified in the Taiwan Strait by satellite images; shipboard measurements demonstrated low water temperature, high Chl-*a* and high salinity in DSU and TBU areas. The shape, intensity center, and size of those upwelling zones are shown to vary during the summer.

4. Discussion

4.1. Five upwelling zones and fishing grounds in the Taiwan Strait

Five distinctive upwelling zones in the Taiwan Strait are identified in this study, all characterized from low water temperature, high Chl-*a* concentrations, and high salinity. Three of them (PTU, MXU, and DSU) are located in the Fujian coastal area, and two of them (TBU and PHU) are in between Fujian coast and Taiwan Island. These upwellings were reported separately in the past. Guan and Chen (1964) first observed an upwelling in the coast near Shantou from observation data of the Chinese Coast Comprehensive Oceanographic Survey (1958–1960); coastal upwelling and TBU were later reported by Hong et al. (1991); Guo (1991) analysed sedimentary environments and proposed wind-driven upwelling in the coastal region and topography-related upwelling in the southern Taiwan Bank. Our study displays all these five upwelling areas at the same time, with results that are largely consistent with previous finding. This study also provides more detailed information by demonstrating the spatial and temporal variation of these upwellings.

These upwelling areas may have different mechanisms. Upward waters of the TBU resulted from different water masses in the southeast and southwest of Taiwan Bank (He, 1991). DSU sometimes extends offshore (Figs. 2 and 3), and it has been regarded as essentially induced by the southwest monsoon (Guan & Chen, 1964). TBU is more permanent due to the bottom topography and northward currents (Hong et al., 1991). Previous observations reported on these upwellings are summarized in Table 1.

Upwelling is not only a hydrology phenomenon, but also has a tremendous impact on ecosystem. High Chl-*a* concentrations indicating high phytoplankton biomass were revealed in these upwellings. Upwelling areas are commonly considered as good fishing grounds due to high primary productivity associated with the upwelled nutrients (Ryther, 1969). Taiwan Bank Fishing Ground was first defined as an upwelling fishing ground in 1991 (Hong et al., 1991; Qiu et al., 1991). Three major fishing grounds in the southern part of Taiwan Strait in summer are shown in Fig. 6 (after Hong et al., 1991): Taiwan Bank Fishing Ground (TBFG), Coastal Fishing Ground (CFG), and Penghu Fishing Ground (PHFG). In summer, TBFG also features a banana shape, as observed in the present study, and CFG is located close to DSU. In other words, our results show that these upwelling zones, particularly DSU and TBU (Figs. 2 and 5), coincide with these fishing grounds with respect to location, size, and shape.

Table 1
Observations of upwelling in the Taiwan Strait

Upwelling	Location	Time of observations	Methods	References	Season of fishing ground (from Hong et al., 1991)
PTU	Nearshore of PTI	June–August	Hydrographic	Xiao, 1988	
PTU	Nearshore of PTI	August 1998	Hydrographic	Li, Hu, & Chen, 2000	
MXU	Between MZ and XM	1980	CZCS data	Tang et al., 1998	
MXU	Between MZ and XM	1998	SST and SeaWiFS	Present study	
DSU	Nearshore ST	May–June 1995	Hydrographic	Guan & Chen, 1964	Summer
DSU	South of ST	July 1988	Multidiscipline	Hong et al., 1991	
DSU	Offshore DSI	August 1984	Hydrographic	Xiao, 1988	
DSU	Nearshore DSI	August 1998	Hydrographic	Li et al., 2000	
PHU	Near PHI	Summer 1988	Biology data	Hong et al., 1991	Spring and summer
PHU	Near PHI	Oct 1997	Hydrographic data	Fan, 1997	
TBU	Southwest of TWB	October–March	Hydrographic	Chen, Fu, & Li, 1982	All year round
TBU	Southeast of TWB	Summer 1982	Hydrographic	Qiu, Huang, Chen, & Guo, 1985	
TBU	South of TWB	Summertime case	Current data	Hu & Liu, 1992	
TBU	Southeast of TWB	All year round	Multidiscipline	Hong et al., 1991	
TBU	South of TWB	Summer and winter cases	Numerical modelling	Yang et al., 1991	

PTU: the coastal upwelling near Pingtan Island (PHI); MXU: the coastal upwelling between Meizhou (MZ) and Xiaman (XM); DSU: big coastal upwelling near Dongshan Island (DSI); TBU: the intensive upwelling in southeast edge of the Taiwan Bank (TWB); PHU: an upwelling near the Penghu Island (PHI).

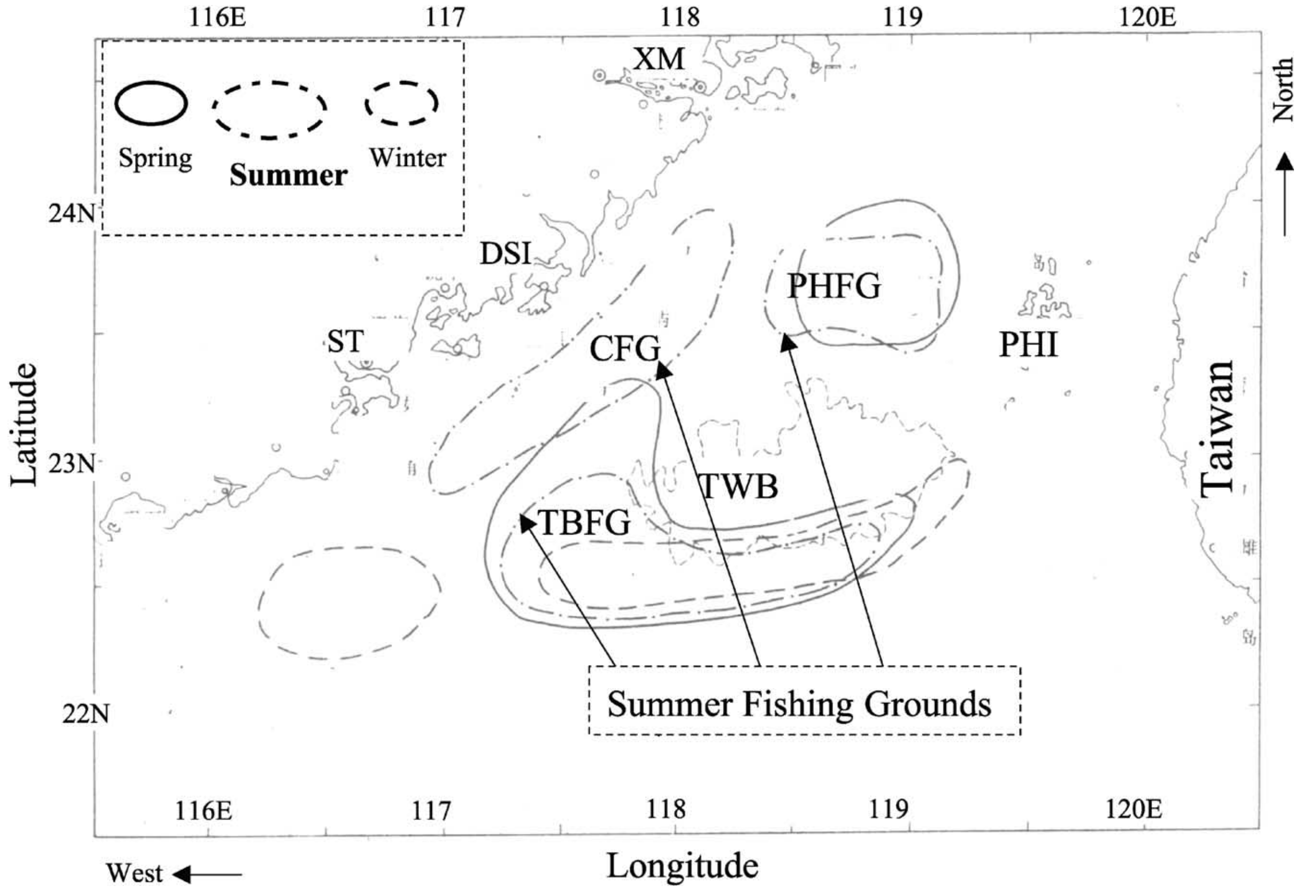

Fig. 6. Three fishing grounds in Taiwan Strait (after Hong et al., 1991, p. 7): (1) CFG: Coastal Fishing Ground; (2) PHFG: Penghu Fishing Ground; and (3) TBFG: Taiwan Bank Fishing Ground. TWB: Taiwan Bank.

Among these five upwelling zones, TBU is noticed: it is large in size, strong in summer, and is the most important fishing ground in the Taiwan Strait.

4.2. Spatial and temporal variation of TBU

Previous studies described summer TBU as follows: (1) it is weak in June, strong in July, and gradually becomes weak again in August (Wu & Lin, 1990). (2) Hong et al. (1991) divided the TBU region as south-western and south-eastern zones because the water sources and their main characteristics are quite different between the two upwelling zones; (3) even today the real feature and formation mechanism of TBU are neither well characterized nor clearly understood.

Several currents may influence Taiwan Bank and TBU in summer. The South China Sea (SCS) Warm Current flows along the continental shelf break northward hitting the Taiwan Bank, the SCS circulation northeastward to Taiwan Strait through the west of the Taiwan Bank, and the Kuroshio intruding water also affect the sea area around Taiwan Bank. Our study was focussed mainly on spatial variations of TBU during summer season. The results indicate that TBU is rather strong in its southwest or southeast edges, and its size can change. It is in agreement with observation reported by Hong et al. (1991), which may resulted from different upwelled waters in different sides of southern Taiwan Bank. The structure of temperature, pigment concentration, and salinity parameters measured in this study all confirm the existence of an upwelling process in this region, which was also documented by others. The intensity of the upwelling in August is most probably due to enhanced vertical mixing, and it is expected to decrease in fall, as a result of an interaction of the South China Sea Warm Current and the shoal area of the Banks (He, 1991; Hu & Fu, 1991). The temporal variation of TBU may also be due to the variation of current systems and movement of the front because the TBU is located at the conjunction of many current systems (Hu & Liu, 1992).

4.3. Satellite remote sensing approach for upwelling study

Studies on upwelling in the Taiwan Strait with satellite images have been very limited (Wang, Hong, Li, & Xu, 1991). Tang et al. (1998) observed high pigment concentrations zones coinciding with upwelling areas in the Taiwan Strait by analyzing CZCS data on the continental shelf of China. The present study gives more detailed examination of SST and Chl-*a* in this area by utilizing various satellites imageries. Different types of satellite data demonstrated consistent results in this study. Upwelling waters with low temperature and high Chl-*a* can be easily identified by satellite, particularly in the summer season. During that season, the temperature on sea surface is high, and therefore upwelled waters of lower temperature can be easily observed. Cruise measurements in summer 1988 shows that there were low water temperature (19.28–21.79 °C) and high salinity (34.43) in the south edge of the TBU zone (Huang, 1991), Chl-*a* concentration reached 2.06 mg m^{-3} on the euphotic zone (Yang, Zhang, & Gao, 1991). However, upwelled water may sometimes climb only up to the subsurface (Huang, 1991), and therefore, the in situ observation during a specific period may not be able to find low temperature waters. Our shipboard measurements (Fig. 4a,b) detected strong evidence of DSU, but did not allow us to prove existence of the TBU. It is because that the cruise did not cross fully the TBU (transect S in Fig. 1b). Satellite data have the advantage of a long-term record over a large area, and they are very useful for characterizing of the location, size, and time series of upwelling processes.

Previous studies provided some information about the location of TBU, but not about the size and shape of this upwelling. The satellite data used in the present study provides, for the first time, reliable information about the size of the TBU and about the temperature difference between upwelling and non-upwelling areas, it also displays a short-term variation of TBU in summer 1998. In the future, long-term continuous observation, at least for a 1-year cycle, from both satellite and shipboard survey would certainly contribute to a better understanding of upwelling process.

5. Summary

Five upwelling zones in the Taiwan Strait have been identified in summer based on low SST, high Chl-*a*, and high salinity, both by satellite and shipboard measurements—these are PTU, MXU, TBU, and PHU. These upwelling zones are somewhat localized, but their size and temperature may vary over a certain period of time. DSU extends to offshore area and sometimes disappears; TBU has a size of 2500–3000 km^2 in summer. During summer time, TBU, DSU, and PHU coincide with fishing grounds with regard to location and shape. This is the first study displaying spatial and short-term variations of Taiwan Bank Upwelling (TBU) by series SST and Chl-*a* images. It is also the first study analyzing, by satellite data, the size of TBU and the temperature difference between upwelling and non-upwelling areas. We were not sure where was the centre of these upwelling during the shipboard measurement until we analyzed the result of this study. The result of this study may guide us for future cruise surveys for both oceanography and fisheries. This study demonstrates the potential of satellite data on upwelling study.

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