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Long-time observation of annual variation of Taiwan Strait upwelling in summer season

D.L. Tang [a,b,c,*], H. Kawamura [a], L. Guan [d]

[a] Center for Atmospheric and Oceanic Studies, School of Science, Tohoku University, Sendai 980 8578, Japan
[b] South China Sea Institute of Oceanology, Chinese Academy of Science, Guangzhou, China
[c] Institute of Hydrobiology, Jinan University, Guangzhou, China
[d] Ocean Remote Sensing Institute, Ocean University of Qingdao, Qingdao, China

Abstract

The Taiwan Strait is between Taiwan Island and Mainland China, where several upwelling zones are well known for good fishing grounds. Earlier studies in the strait have been conducted on detecting upwelling by ship measurements with short-term cruises, but long-term variations of upwelling in this region are not understood. The present paper examines satellite images for a long-time observation of two major upwelling zones in the Taiwan Strait: Taiwan Bank Upwelling (TBU) and Dongshan Upwelling (DSU). Sea surface temperature (SST) and chlorophyll a (Chl-a) images have been analyzed for summer months (June, July, and August) from 1980 to 2002. Results reveal annual variation of two upwelling zones. These two upwelling zones occur every year characterized with distinct low water temperature and high Chl-a concentrations. During the period from 1989 to 1998, SST is found to be 1.15 °C lower in TBU, and 1.42 °C lower in the DSU than the Taiwan Strait. The size of DSU has been found to be larger during summer of 1989, 1990, 1993 and 1995; TBU has been found to be weak during summer of 1994 and 1997. Ocean color images obtained from CZCS, OCI, and SeaWiFS also show high Chl-a concentrations (0.8–2.5 mg m^{-3}) in two upwelling zones, which coincide with low SST in terms of location, shape, and time. These high Chl-a concentrations in TBU and DSU may be related to upwelling waters that bring nutrients from bottom to surface. The present results also show the potential of using satellite data for monitoring of ocean environment for long time period.

Keywords: Taiwan Strait; Upwelling; AVHRR SST; SeaWiFS; Chl-a; China

1. Introduction

Upwelling is a term describing the processes that causes the upward movement of sea water from deeper layer into the surface layer. Upwelling areas in the Taiwan Strait are famous fishing grounds (Hong et al., 1991). A better knowledge about inter-annual variation of upwelling in the Taiwan Strait is essential for fishery resource and coastal environment management. The present study reports observation of annual variation of upwelling in the Taiwan Strait by analyzing remote sensing data obtained from satellite.

An early observation in China oceans indicated upwelling zones in the Taiwan Strait by using hydrographic data obtained from Chinese coast comprehensive oceanographic survey (1958–1960) (Guan and Chen, 1964). More studies on the Taiwan Strait were conducted using ship measurements by Xiaman University (Hong et al., 1991). Five upwelling zones have been observed in the Taiwan Strait in summer 1998 by analyzing satellite data and ship measurements (Tang et al., 2002). Among these, Taiwan Bank Upwelling (TBU) and Dongshan Upwelling (DSU) have got more attentions because of large size and good fishing grounds. Tang et al. (1998) have found annual variations of pigment concentration in the Taiwan Strait during 1978–1986, and have reported short-term variability of TBU in August 1998 (Tang et al., 2002). However, in the Taiwan Strait, most previous studies have focused on detecting upwelling zone from ship measurements (Wu and Lin, 1990; Hong et al., 1991; Lin

* Corresponding author.
E-mail address: lingzistdl@yahoo.com (D.L. Tang).

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et al., 1992), and limited studies have utilized satellite images (Lin et al., 1992; Tang et al., 2002), long-term variations of upwelling in this region are not understood yet. The study on inter-annual variation of these upwelling zones is lacking because there has been no long-time oceanography monitoring in the Taiwan Strait.

Satellite remote sensing with repeated coverage and long-term time record is the most efficient method for monitoring oceanic process. Ocean color images and Advanced Very High Resolution Radiometer (AVHRR) Sea Surface Temperature (SST) data have been used to detect upwelling in the Taiwan Strait in 1998 (Tang et al., 2002). SST data have also been used to detect thermal plume from a power station in Daya Bay, in the southeast of the Taiwan Strait, in the South China Sea (Tang et al., 2003). By analyzing both ocean color, chlorophyll a (Chl-a) data and AVHRR SST data, Tang et al. (1999) observed phytoplankton blooms related to upwelling area southwest of the Luzon Strait in the South China Sea. The present paper studies annual variation of TBU and DSU in the Taiwan Strait by analyzing satellite images of AVHRR SST and Chl-a obtained in summer during 1980–2002.

2. Study area and methods

2.1. Taiwan Strait and data sampling stations

Taiwan Strait is between Taiwan and Mainland China, located at the confluence of the East China Sea and the South China Sea in the west Pacific Ocean (Fig. 1(a)). The Taiwan Strait has complex bottom topography. Its width is about 170–370 km and its length is 330 km, with 50–70 m in depth over much of its extent. In the strait, the depth is less than 50 m along the Fujian coast (Fig. 1(a)), and a shoal area of 15–20 m at the Taiwan Bank (TBU in Fig. 1(b)) (23°N, 118–119°E).

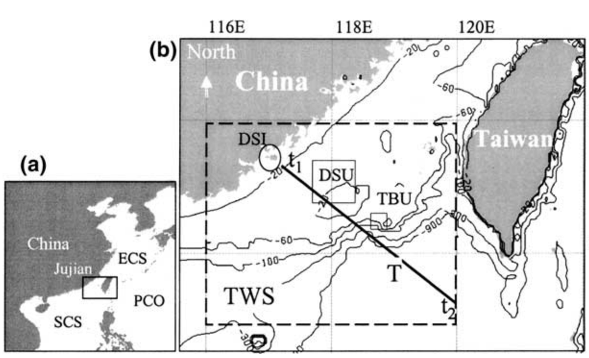

Fig. 1. Location (a) and bathymetric chart (b) of the study area. ECS: East China Sea; PCO: Pacific Ocean; SCS: South China Sea; DSI: Dongshan Island. DSU: Dongshan Upwelling; TBU: Taiwan Bank Upwelling; T: Transect for SST data sampling; TWS: Area for SST data sampling.

DSU is located along the Fujian coast, and TBU on the Taiwan Bank.

Transect *T* (*T* in Fig. 1(b)) is designed for SST data sampling from northwest (t_1: 23.77°N, 117.82°E) near Dongshan Island (DSI in Fig. 1(b)) to southeast (t_2: 21.31°N, 120.54°E), crossing through DSU and TBU. Other three regions are also selected for SST data sampling: TBU (Fig. 1(b)) (22.98°N, 118.78°E), DSU (Fig. 1(b)) (23.2°N, 118.23°E), and TWS (Fig. 1(b)) area (21–24°N, 116–120°E). TWS is in the southern part of the Taiwan Strait, including both TBU and DSU zones.

2.2. AVHRR SST data from NOAA satellite

Monthly averaged SST data have been obtained from the Pathfinder SST data provided by NASA/JPL (Kilpatrick et al., 2001). These are the best images of global coverage with 9 km (4096×2048) spatial resolution processed through NLSST algorithm version 4.1 (Walton, 1988). We have sampled SST data for 32 pixels from t_1 to t_2 along transect *T* (Fig. 1(b)) for summer season (June, July, and August) from 1987 to 1998.

For a comparative study among upwelling zones and the surrounding waters, we have sampled 1 pixel SST data (9 km $\times$ 9 km) for TBU (box TBU in Fig. 1(b)), 3 pixels SST data (27 km $\times$ 27 km) for DSU (box DSU in Fig. 1(b)), and SST data for TWS area (box TWS in Fig. 1(b)) (46×35 pixels) for July from 1987 to 1998. The averaged SSTs have been calculated for these three regions. The SST differences among three regions have also been analyzed.

2.3. Satellite ocean color data

Coastal Zone Color Scanner (CZCS) images with spatial resolution of 4×4 km^2 have been produced by NASA. The standard atmospheric and bio-optical algorithms (Gordon et al., 1983) have been used to correct for aerosols, cloud cover, and sun glint. We have archived monthly average CZCS derived pigment concentration images in the remote sensing laboratory at the University of South Florida (Tang et al., 1998, 1999).

ROCSAT-1 is a low-earth orbit experimental satellite launched in the early 1999 in Taiwan. Ocean Color Image (OCI) has been carried on ROCSAT-1, it is an all-refractive spectral-radiometer that has six spectral bands spinning from visible to near infrared (Liu et al., 2000). The OCI derived Chl-a images with 1 km spatial resolution have been obtained from the OCI data distribution center in the National Taiwan Ocean University, Keelung, Taiwan (OCI-SSDDC, 2002).

Sea-viewing Wide Field-of-View Scanner (SeaWiFS) was launched onboard the Orbview-2 satellite in August 1997. SeaWiFS derived Chl-a images of 1 km spatial resolution of local coverage have been processed by

SEADAS with the standard atmospheric correction and OC4 algorithm (O'Reilly et al., 1998) at Asian I-Loc Project (Tang et al., 2002; Tang and Kawamura, 2002).

3. Results and discussion

3.1. Annual variation of SSTs in two upwelling zones

Monthly average SSTs in the Taiwan Strait for July is shown in Fig. 2(a)–(l). The spatial pattern of SST in 12 years shows high SST (around 28–30 °C) evenly distributed in the Taiwan Strait, and two distinct zones of low SST (25–27 °C) are clearly seen in DSU and TBU areas. DSU zone is half-round shape near the coast of China, whereas TBU zone shows banana shape in the southern edge of the Taiwan Bank (Fig. 2(b)).

We have also observed annual variation of DSU and TBU during 1978–1998. SST of DSU was lower during summer 1990, 1993 and 1995 (Fig. 2(d), (g), and (i)); TBU was weak in 1994 and 1997 (Circles in Fig. 2(h) and (k)). Northwestward warm water (white arrows) from the South China Sea is found to have high temperature during July 1987, 1989, and 1996 (Fig. 2(a), (c), and (j)), cold water (black arrows) along the coast of China in the Taiwan Strait is found to be strong during July 1993 and 1995 (Fig. 2(g) and (i)). SST is found to be lower in the whole area during July of 1992 (Fig. 2(f)).

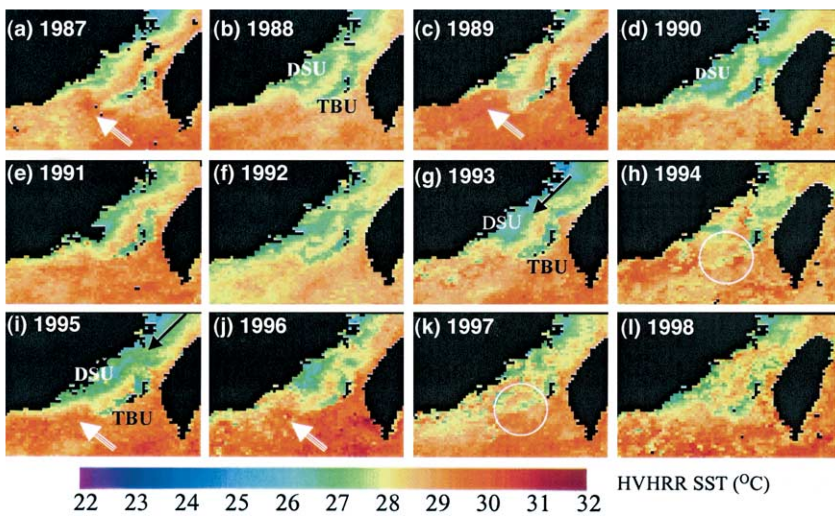

Fig. 2. (a–l) Monthly average sea surface temperature (SST) maps for July from 1978 to 1998 in the Taiwan Strait. Lands and cloudy areas are shown in black color. Spatial resolution is 9 × 9 km. Color bar indicates SST (°C). DSU: Dongshan Upwelling; TBU: Taiwan Bank Upwelling.

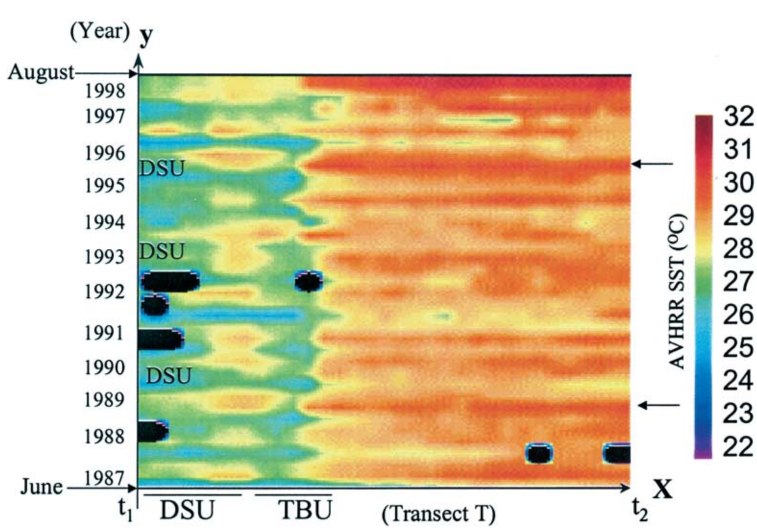

Fig. 3. Time series of AVHRR SST along transect T (T in Fig. 1(b)) from t_1 to t_2 in summer months (June, July, and August) during 1987–1998. Color bar indicates SST (°C). Cloudy areas are shown in black color. DSU: Dongshan Upwelling; TBU: Taiwan Bank Upwelling.

3.2. SST difference among upwelling zones and the Taiwan Strait

Fig. 3 shows SSTs in two upwelling zones along transect *T* for summer months (June, July, and August) from 1987 to 1998. Low SST has been observed in two zones in t_1 side (China coast), and high SST is observed in t_2 side (Taiwan coast). Low SST over DSU zone is observed extending eastward to TBU in 1991, 1995, and 1996; strong warm SST from South China Sea is observed during 1989 and 1996 (arrows in right side).

We have also examined SST differences among two upwelling zones and the Taiwan Strait (TWS in Fig. 1(b)). Over these 12 years, SST was lower in DSU (Fig. 4(a)) than in TBU (Fig. 4(b)). Two upwelling zones had similar features of annual changes: the SST differences between upwelling zone and the Taiwan Strait were large during July 1989 (1.5 and 2.5 °C) and 1996 (1.5 and 2.0 °C) and small in 1994 (0.75 and 0.75 °C) (Fig. 4); The average value of SST difference in July was 1.15 °C between TBU zone and the Taiwan Strait, and 1.42 °C between DSU zone and the Taiwan Strait during 1987–1998.

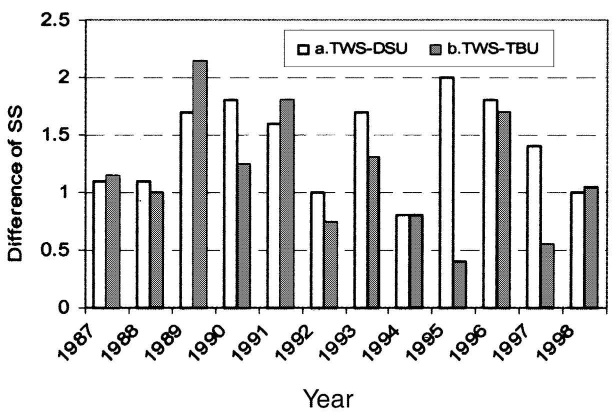

Fig. 4. SST differences among upwelling zones and the Taiwan Strait (TWS) in July from 1987 to 1998. (a) SST differences between TWS and DSU (Dongshan Upwelling); (b) SST difference between TWS and TBU (Taiwan Bank Upwelling).

3.3. High Chl-a concentrations in two upwelling zones

The monthly average pigment/Chl-a concentrations in the Taiwan Strait have been obtained from several satellites. The CZCS-derived image obtained in June 1980 (Fig. 5(a)) shows high monthly average pigment contents in TBU regions with a banana-shape along southeast adage of the Taiwan Bank, and in DSU region. Fig. 5(b) is a SeaWiFS-derived Chl-a image, showing very strong Chl-a concentration in two upwelling zones during August 1998. OCI image (Fig. 5(c)) for August 1999 shows high Chl-a content in TBU zone although the coverage of this image is not good for the coastal area.

Fig. 5(d)–(f) show SeaWiFS derived Chl-a during 2000, 2001, and 2002. High Chl-a of half-round shape is clearly observed in DSU along the China coast; In TBU zone, high Chl-a concentrations is found along the southeast edge of the Taiwan Bank (two arrows in Fig. 5(d) and (f)). The sizes of two upwelling zones have been found to be large during August 2000 and 2002 (Fig. 5(d) and (f)) with two intensive centers in TBU (two arrows in Fig. 5(f)).

3.4. Characters of two upwelling zones

Low water temperature is one of the indicators of upwelling, and SST difference between upwelling zone and the surrounding waters is one of the parameters for defining upwelling intensity (Kuo et al., 2000; Tang et al., 2002). The present study provides some details for

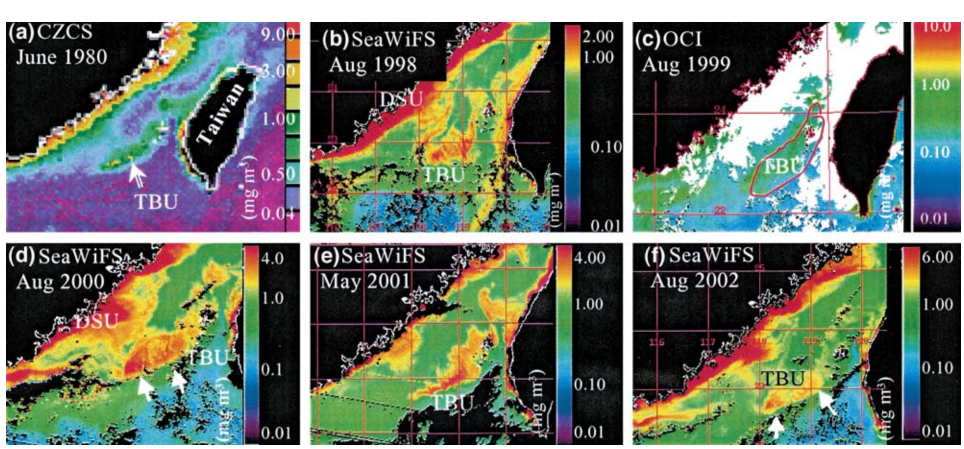

Fig. 5. Satellite measurements of Chl-a in the Taiwan Strait in spring–summer months from 1980 to 2002. Color bars indicate Chl-a concentrations (mg m^{-3}). Lands and cloudy area are shown in black color. CZCS: Coastal Zone Color Scanner; OCI: Ocean Color Image; SeaWiFS: Sea-viewing Wide Field-of-View Scanner.

SST and Chl-a on the two upwelling zones in the Taiwan Strait.

Our result show two intensive centers of Chl-a in the southern part of the TBU (Fig. 5(f)), which may indicate different water sources. It is in agreement with the observation reported by Hong et al. (1991). Hong described TBU region as south-western and south-eastern zones because the water sources and the main characteristics are quite different between the two zones. Upwelling waters of the TBU may originate from different water masses in the southeast and southwest of Taiwan Bank (He, 1991).

Low SST has been observed in north of DSU zone (Fig. 2(g) and (i)) in 1993 and 1995, which may indicate upwelling along the whole coastal area, including other two upwelling zones in the northwest of the strait (Tang et al., 2002). High Chl-a concentrations indicating phytoplankton blooms have been also reported southwest of the Luzon Strait in the south China Sea, these phytoplankton blooms were related to upwelling which brings nutrients to the surface water and lowers the water temperature (Tang et al., 1999).

DSU and TBU may have different mechanisms. DSU zone has been regarded as essentially induced by the southwest monsoon (Guan and Chen, 1964), and TBU zone is more permanent due to the bottom topography and northward currents (Hong et al., 1991). Guo (1991) reported that the coastal upwelling (DSU) was a wind driven upwelling and the TBU was topographic upwelling. Therefore these two upwelling zones with different patterns of temporal variation may reflect influences of monsoon and currents. By analyzing annual composite images of CZCS data, Tang et al. (1998) have found high values of pigments in the Taiwan Strait during 1979 for the period from 1979 to 1986. Short-term variation of SST in TBU in August 1998 was reported later (Tang et al., 2002), showing both DSU and TBU zones change their size and intensive centre from time to time.

3.5. Inter-annual variation of upwelling

The present results show an inter-annual variation in these two upwelling zones. Two upwelling zones show similarly patterns of inter-annual variations over these years. The annual variation may reflect several factors due to varying mechanisms for different upwelling zones. In term of low SST, both DSU and TBU showed great SST gradients in 1989 and 1996 (Fig. 2), this might be because of strong warm water from the South China Sea (Fig. 2(c) and (j)), which enhanced SST differences between upwelling zone and the surrounding waters. Further investigations are required to understand these mechanisms.

Upwelling is not only a hydrological phenomenon, but also has tremendous impact on ecosystem. During summer season, TBU and DSU zones coincide well with fishing grounds in terms of location and shape (Tang et al., 2002). This is again supported by the present study. The present results show high Chl-a concentrations in two upwelling zones (Fig. 5), indicating well growing phytoplankton due to the nutrients brought up from the bottom to the surface in the upwelling areas. More investigations will be interesting to understand if annual variations of upwelling affect annual fishing production in the Taiwan Strait.

4. Conclusion

Several satellite data (AVHRR, CZCS, SeaWiFS, OCI) have been used to study the annual variations of DSU and TBU zones in the Taiwan Strait during summer season. Short time variation of Taiwan Strait upwelling zones have been studied earlier, the present paper shows inter-annual variation of these upwelling zones by examining remote sensing data obtained from several satellite; it is the first study of using OCI data on this region. The present study demonstrates the potential of satellite data on upwelling monitoring for a long time period.

The present results show low water temperature in two upwelling zones; SST images show large size of DSU zone during 1989, 1990, 1993, and 1995, and weak TBU in 1994 and 1997; Variations of SST in DSU is found to be larger compared to TBU zone. SeaWiFS images show further strong upwelling evidence in two upwelling zones during August 2002. Two intensive centers in TBU have also been observed. Detailed investigations on oceanography and effect of upwelling on ecology are required for better understanding of inter-annual variation of and their affect on annual fishing production in the Taiwan Strait.

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