Available online at www.sciencedirect.com
SCIENCE DIRECT®
Remote Sensing of Environment 84 (2003) 506–515
Remote Sensing of Environment
www.elsevier.com/locate/rse

# AVHRR satellite remote sensing and shipboard measurements of the thermal plume from the Daya Bay, nuclear power station, China

DanLing Tang[a,b,c,*], Dana R. Kester[b,c], Zhaoding Wang[d], Jiansheng Lian[d], Hiroshi Kawamura[a]

[a] Center for Atmospheric and Oceanic Studies, Tohoku University, Sendai, Japan
[b] Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, USA
[c] Institute for Environment and Sustainable Development, The Hong Kong University of Science and Technology, Hong Kong, China
[d] Marine Biological Research Station at Daya Bay, The South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China

Received 27 May 2002; received in revised form 26 August 2002; accepted 9 September 2002

**Abstract**

The 1800 MW Daya Bay Nuclear Power Station (DNPS), China's first nuclear power station, is located on the coast of the South China Sea. DNPS discharges 29 $10 \times 10^5$ $m^3$ $year^{-1}$ of warm water from its cooling system into Daya Bay, which could have ecological consequences. This study examines satellite sea surface temperature data and shipboard water column measurements from Daya Bay. Field observations of water temperature, salinity, and chlorophyll *a* data were conducted four times per year at 12 sampling stations in Daya Bay during January 1997 to January 1999. Sea surface temperatures were derived from the Advanced Very High Resolution Radiometer (AVHRR) onboard National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites during November 1997 to February 1999. A total of 2905 images with $1.1 \times 1.1$ km resolution were examined; among those images, 342 have sufficient quality for quantitative analysis. The results show a seasonal pattern of thermal plumes in Daya Bay. During the winter months (December to March), the thermal plume is localized to an area within a few km of the power plant, and the temperature difference between the plume and non-plume areas is about 1.5 °C. During the summer and fall months (May to November), there is a larger thermal plume extending 8–10 km south along the coast from DNPS, and the temperature change is about 1.0 °C. Monthly variation of SST in the thermal plume is analyzed. AVHRR SST is higher in daytime than in nighttime in the bay during the whole year. The strong seasonal difference in the thermal plume is related to vertical mixing of the water column in winter and to stratification in summer. Further investigations are needed to determine any other ecological effects of the Daya Bay thermal plume.


*Keywords:* Thermal plume; Water temperature; Remote sensing; AVHRR; Nuclear power station; Daya Bay; South China Sea

## 1. Introduction

The Daya Bay Nuclear Power Station (DNPS) is the first nuclear power station and the largest foreign investment joint project in China. The Daya Bay project marks the first step taken by China in the development of large-capacity commercial nuclear power units (Zeng, 1994). DNPS is situated on the north shore of Dapeng Cove in the southwest portion of Daya Bay. It is located about 30 km from Hong Kong and about 60 km from the Shenzhen Special Economic Zone (Tso & Li, 1992). DNPS has been operational since February 1994. It discharges seawater from its cooling system at the rate of 95 $m^3$ $s^{-1}$, and $290 \times 10^4$ $m^3$ $year^{-1}$ (Chen, Shi, & Mao, 1996; Zang, 1993; Zheng, He, & Zhang, 1998). Warm seawater discharge could have consequences on the ecology of the Daya Bay (Huang, Zhu, Xu, & Jing, 1998). But until now we do not know the spatial and temporal distribution of the warm water discharge from the power station. The objective of this study is to test the feasibility of characterizing the thermal plume of the DNPS using Advanced Very High Resolution Radiometer (AVHRR) satellite remote sensing.

Daya Bay is located at 22°30′–22°50′N, 114°30′–114°50′E, in the northern South China Sea. It is one of a series of large embayments along the southern coast of China and covers an area of 550 $km^2$ with a width of about 15 km and a north–south length of about 30 km (Fig. 1). About 60% of the area in the Bay is less than 10 m deep (Xu, 1989). Dapeng Cove, in the southwest portion of

* Corresponding author. Center for Atmospheric and Oceanic Studies, School of Science, Tohoku University, Sendai, 980-8578, Japan. Tel.: +81-22-217-6744; fax: +81-22-217-6748.
*E-mail address:* lingzis@ocean.caos.tohoku.ac.jp (D.L. Tang).

0034-4257/02/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0034-4257(02)00149-9

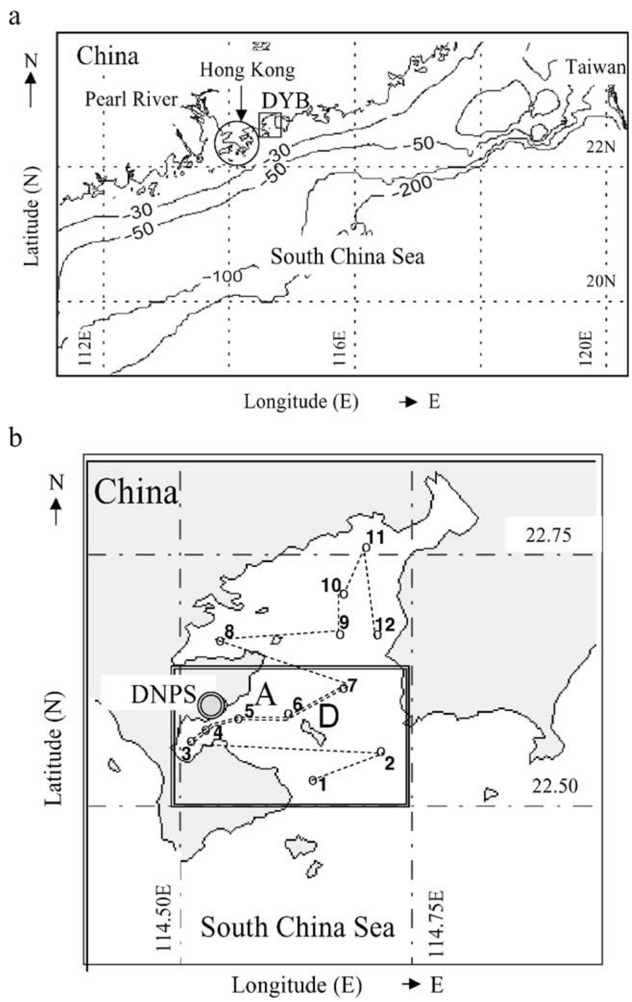


Fig. 1. Maps of research area. (a) Chart of the study area in the northern area of the South China Sea (the bathymetry was derived from TerraScan satellite imagery processing software and data files). DYB: Daya Bay-satellite data sampling area. (b) Daya Bay map with the Daya Bay Nuclear Power Station (DNPS) in Dapeng Cove. Twelve survey stations are shown in Daya Bay. Transect A (between stations 3 and 7) is for the survey measurements in July 1998. The double-lines box covering Dapeng Cove and the southern portion of Daya Bay is the area for satellite data analysis of the thermal plume and non-plume pixels. The double-circles indicates the location of DNPS; D—Dalakok.

Daya Bay, is about 4.5 km (N–S) by 5 km (E–W). Located in a subtropical region, Daya Bay's annual mean air temperature is 22 °C. The coldest months are January and February, with a monthly mean air temperature of 15 °C, and the hottest months are July and August, with a monthly mean air temperature of 28 °C. The sea surface temperature is the lowest in spring (15 °C) and highest in summer and fall (30 °C) (Xu, 1989). No major rivers discharge into Daya Bay, and most of its water originates from the South China Sea.

The oceanography of Daya Bay has been studied extensively, notably for obtaining environmental information related to the siting and operation of the nuclear power station (Wen, He, & Zhen, 1992). Studies have also been conducted on the bay's overall ecology, especially by the Marine Biological Research Station (MBRS), which is located on the south shore of Dapeng Cove. The South China Sea Institute of Oceanology, Chinese Academy of Sciences, which operates the MBRS, conducts surveys of the Daya Bay four times per year (Han, 1991; Pan & Cha, 1996; Pan & Wang, 1998). These surveys typically include the measurement of the physico-chemical parameters of the seawater and the composition and biomass of the biota at twelve stations within the bay. Vertical mixing is strong in winter, and the water column becomes stratified in summer (Han, 1991). The temperature and salinity of Daya Bay before the operation of DNPS were reported in 1990 (Zhan, Zeng, & Li, 1990). During the summer season, seawater with lower temperature and higher salinity intruded at depth into the bay (Li, Zhang, & Zeng, 1990). Huang et al. (1998) performed a comparative study of water temperature at twelve stations before and after the starting up of the DNPS. They found that since the opening of DNPS, the annual mean water temperature has increased by 0.34 °C. The greatest recorded change in water temperature was 2.30 °C in summer. Zheng et al. (1998) studied changes in the chemical composition of the seawater from waste water discharged into Daya Bay. There also have been some studies in the bay using Landsat TM satellite remote sensing (Chen et al., 1996; Li, Xu, & Yi, 1990). The use of AVHRR sea surface temperature (SST) can provide additional information on the spatial and seasonal variation in the Daya Bay, which cannot be provided by a limited number of ship stations and surveys.

Kester and Fox (1993) summarized the seasonal cloud-cover characteristics of the South China Sea region and their effect on visible satellite remote sensing using the Coastal Zone Color Scanner data set. AVHRR data have been utilized successfully for studies on SST distribution pattern on many areas, such as Hong Kong waters (Tang & Ni, 1996), the Taiwan Strait (Tang, Kester, Ni, Kawamura, & Hong, 2002b), and the Arabian Sea (Tang, Kawamura, & Luis, 2002). Through examination of AVHRR images, Tang and Ni (1996), Tang et al. (2002b) studied spatial and temporal changes of the sea surface temperature in Hong Kong waters, Taiwan Strait, and in the northern waters of the South China Sea. They reported that the China Coastal Current and South China Sea Drift affected water temperature at the mouth of Daya Bay. Previous studies by Kester, Fox, Magnuson, and Andrews (1996) in Narragansett Bay, RI, USA, have shown that SST values can be extracted from nearshore regions of estuaries provided there is 2–3 km of open water between shorelines. AVHRR satellite remote sensing images have a nominal resolution of $1.1 \times 1.1$ km for each pixel in the image. This resolution is adequate to determine SST values from within Daya Bay, Dapeng Cove, and other nearshore portions of the bay. No previous study has examined the spatial and temporal distribution of the warm water discharge from the power station in the Daya Bay using satellite AVHRR data.

In this study, we demonstrate that AVHRR satellite remote sensing images can be used to determine warm water discharge from Daya Bay nuclear power station. We also analyze the monthly and seasonally variability of the thermal plume by using satellite data and ship survey measurements. A second nuclear power reactor is presently under construction at DNPS. When this unit comes online, it will increase the electrical power production in Dapeng Cove from the present capacity of 1800 up to 5800 MW. The present study will be useful in determining the SST distribution in Daya Bay prior to this increased capacity. The results of this work may also help in designing future ecosystem impact assessments.

## 2. Methods

### 2.1. Satellite SST data

The AVHRR images were processed to obtain maps of 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 pixels by 680 pixels array, the SST values were represented by an 8-bit integer (a value between 0 and 255). The TerraScan SST Algorithm is MCSST based (McClain, Pichel, & Walton, 1985). These correspond to sea surface temperatures covering the range of 0–32 °C with a resolution of 1/8 °C. The images were obtained from the receiving station at the Hong Kong University of Science and Technology. NOAA normally maintains two operational polar orbiting satellites that provide SST from AVHRR instruments. One of these satellites has an equator crossing at about mid-day and about midnight local time. The other satellite has equator crossings in the early morning and the late afternoon. When this study began, the NOAA-12 and NOAA-14 satellites were active and crossed over Hong Kong at about GMT 06, 10, 18 and 22 h, which corresponded to the local times of 14, 18, 02 and 06 h. The addition of the NOAA-15 satellite, which was launched on 26 October 1998, increased the maximum number of passes to six per day for a portion of this work. There were times when data from a pass was not usable due to the angle of view from the satellites.

A sampling box (22.85°N, 114.40°E; 22.30°N, 115.0°E) within the images was established for Daya Bay (DYB in Fig. 1a and b). All images of Daya Bay for the period November 1997 to June 1999 were examined. We categorized each image according to its quality for SST analysis into one of six groups designated A (for the best quality) to F (for the worst). Factors that entered into this quality judgment included the presence of clouds and image degradation, possibly caused by atmospheric effects.

A small box (22.65°N, 114.50°E; 22.50°N, 114.75°E) (double-line box in Fig. 1b) in each image was established to test for the presence and extent of a thermal plume. The box covers the lower part of Daya Bay plus Dapeng Cove and the location of the nuclear power station. We then estimated the areal extent of the plume, along with the temperature difference (1–2 °C) between the plume and non-plume areas by using Windows Image Manager (WIM) software (Kahru, 1999). WIM is an image display and analysis program for use with Microsoft Windows operating systems that is particularly useful in the analysis of satellite images. The software can perform various numerical and statistical analyses on the image pixels, can apply masks, detect edges, and other functions that facilitate the analysis and interpretation of satellite images.

We selected a valid data range with upper and lower limits to identify pixels that were within a normal temperature range (non-plume pixels), and those that were warmer than normal (designated as plume pixels). Land pixels were flagged with values of zero and excluded from the analysis. The average temperatures were calculated for pixels in the plume and non-plume areas. The number of pixels in the plume was used to estimate the areal extent of the plume assumes. One pixel is 1.1 × 1.1 $km^2$. The maximal SST (the pixel with maximal SST in the image) in the thermal plume is also recorded for every image during the study period. Monthly average of mean SST and maximal SST of the plume were calculated for each month, we then compared mean SST obtained from daytime (7 am to 7 pm) images and nighttime (7 pm to 7 am) images in the thermal plume. We got 133 images obtained on daytime, and 293 images obtained at nighttime.

### 2.2. Survey measurements

Surveys of the water column properties in Daya Bay were conducted four times per year. We collected data from a total of 12 stations (Fig. 1b) distributed on the whole Daya Bay area from southern part to northern part. Station 4 is the

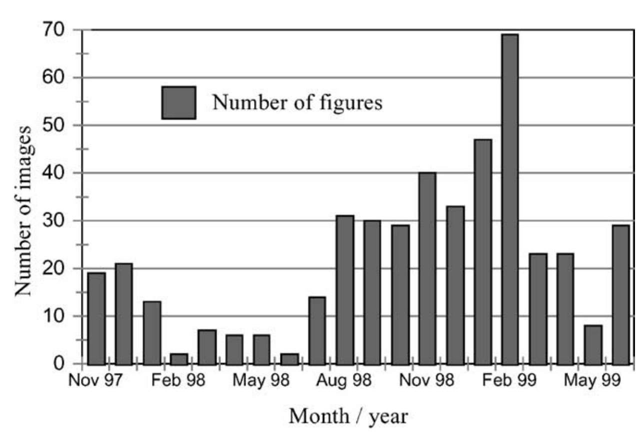


Fig. 2. Number of images during each month used for this analysis. They were judged to be of A or B quality (cloud-free and without artifacts due to poor atmospheric conditions).

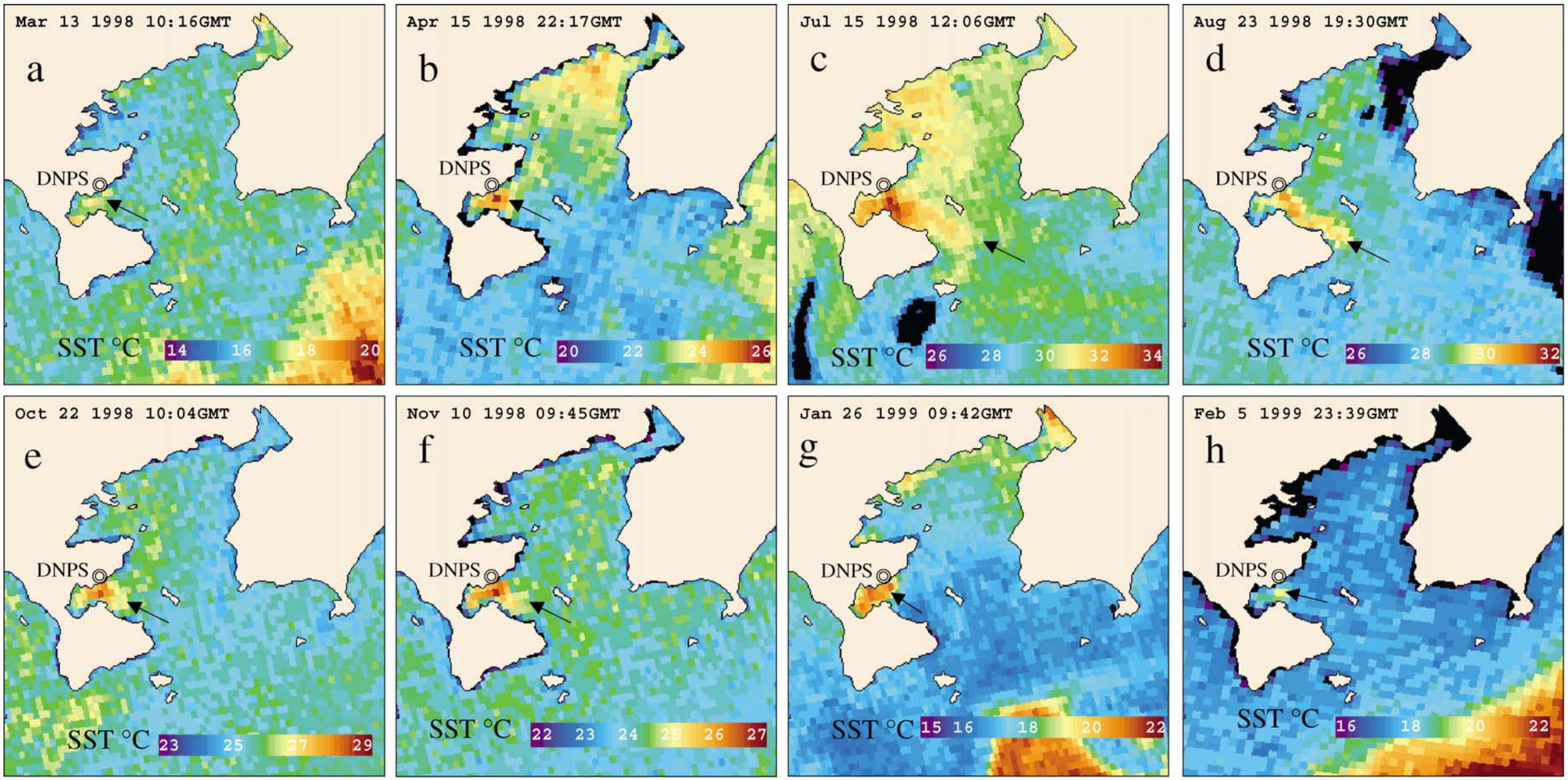


Fig. 3. AVHRR images (of 1 km resolution) showing seasonal thermal patterns in Daya Bay. Double-circles indicate the location of the power station (DNPS); color bars with different ranges show sea surface temperature (SST). (a) March 1998; (b) April 1998; (c) July 1998; (d) August 1998; (e) October 1998; (f) November 1998; (g) January 1999; (h) February 1999.

nearest to the cooling water inlet of the DNPS, and station 5 is the nearest to the outlet. In this study, we used data collected during January, April, July and October 1997 and 1998, plus January 1999. Water temperature, salinity, and chlorophyll *a* (Chl *a*) concentrations were measured both on the surface (in the upper 0.5 m in water) and the bottom (1 m above the bottom).

Surface water temperature and salinity were examined for these 12 stations covering the whole Daya Bay area during the period between January 1997 and October 1998. Water temperature, salinity data were examined for the transect A (from station 3 to station 7) (Fig. 1b) that is along the northern coast of the Daya Bay near the inlet and the outlet of the DNPS. Seasonal variation in temperature and salinity in both surface and bottom water were examined at station 4 for a 1 year period (January 1998 to January 1999).

## 3. Results

### 3.1. AVHRR SST image quality

We have examined a total of 2905 images covering Daya Bay from 3 November 1997 to 30 June 1999. Among those images, 342 were judged to have A or B quality and were

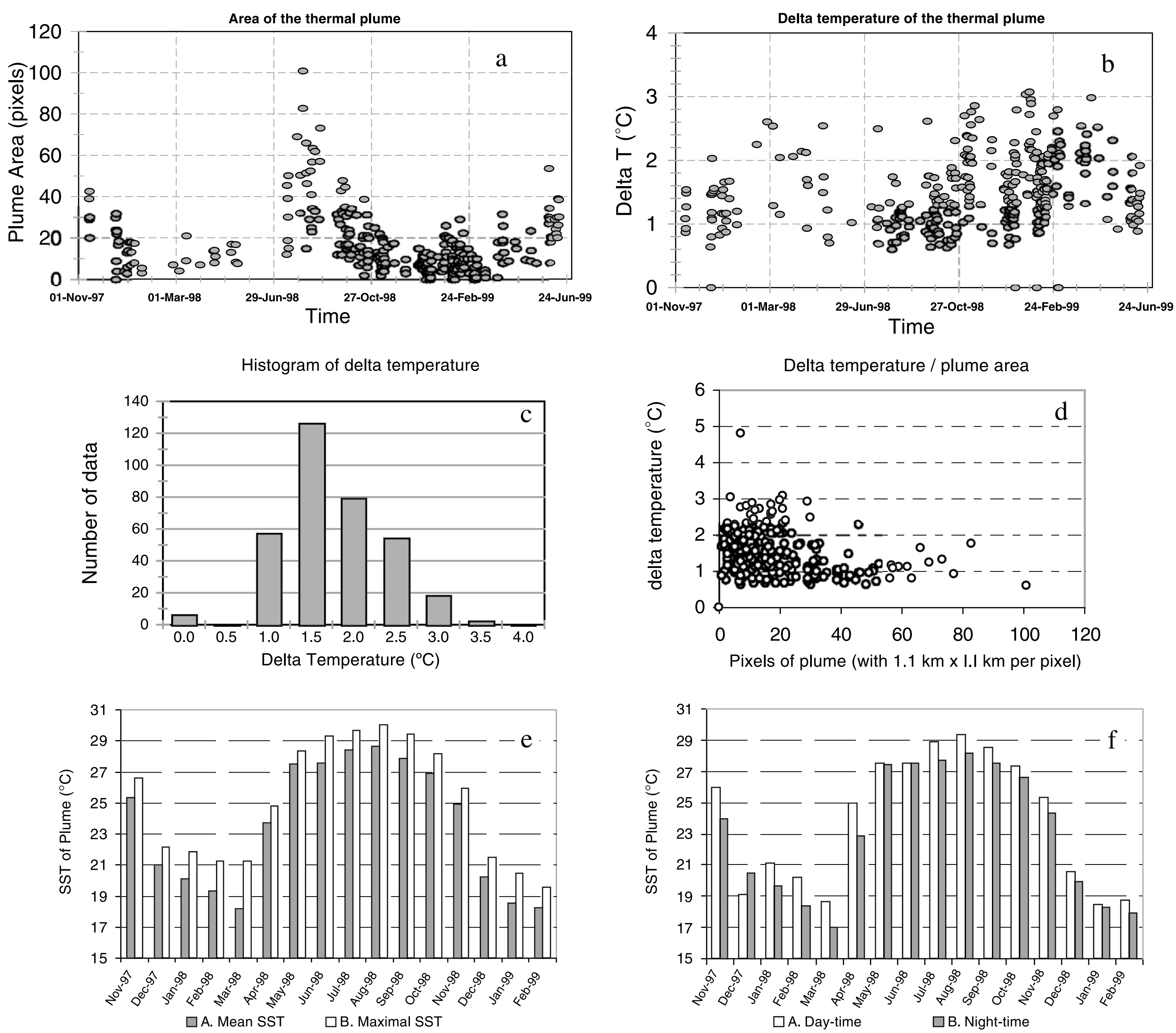


Fig. 4. Time series of the thermal plume from November 1998 to June 1999. (a) Area of plume (pixel = 1.1 × 1.1 $km^2$) from November 1997 to June 1999. (b) Temperature difference (delta *T*) between the plume and non-plume areas from November 1997 to June 1999. (c) Histogram of the delta *T* values using bin ranges of 0.5 °C. (d) Area of plume against delta temperature between plume and non-plume areas. (e) Monthly variation SST of the thermal plume: (A) mean values of SST in the thermal plume; (B) the maximal values of SST in the thermal plume; (f) The differences of mean SST between daytime (A) and nighttime (B) in the thermal plume.

used for quantitative analysis. The number and the quality of SST images varied from month to month. The best month was February 1999 with a total of 149 images, among which 69 could be ranked in category A. There were 87 images for June 1998, but only two images were good enough for quantitative analysis. The number of usable images improved from June 1998 to February 1999 because of the launch of NOAA satellite-15 in late 1998. Fig. 2 shows the number of images that were used for the quantitative analysis.

### 3.2. Remote sensing observations

A set of eight AVHRR SST images, one from each month from March 1998 to February 1999, illustrates the water temperature distribution in Daya Bay and the spatial patterns of the thermal plume from the power station (Fig. 3a–h). Double circles in Fig. 3 indicate the location of the power station (DNPS); color bars show SST. For a better display, we used color bars with different scales to show SST in different seasons. Fig. 3a–h are SST images of 1.1 × 1.1 km resolution. Local time is "GMT + 8" as shown on these images.

The thermal plume showed clearly in spring (March to May). The SST in Daya Bay is low (17–18 °C), but there was a small high-temperature (19–20 °C) area (arrow in Fig. 3a and b) immediately adjacent to DNPS, which spread southwestward into the Daya Bay. Fig. 3a and b show SST in March and April 1998. These two images also indicate high SST in the South China Sea, which can be seen in the southeastern part (red and yellow color) in the two figures. Water temperature increases in the whole Daya Bay in summer. The thermal plume is larger during June to August (Fig. 3d), and reaches its peak size in July (Fig. 3c) when there is a substantial warm plume extending along the south coast eastward from the DNPS. In autumn (September to November), SST is about 25–26 °C evenly distributed in the whole bay (Fig. 3e,f); the thermal plume with higher temperature (27–29 °C) reaches the south coast of Dapeng Cove and spreads southeastward along the south coast or just around DNPS. The thermal plume is still large in September, but its size decreases in October (Fig. 3e) and November (Fig. 3f). During the winter months (December to February), SST is about 15–17 °C in the bay, lower than in the South China Sea (19–20 °C); the thermal signal is either very localized to within a few pixels (Fig. 3g,h) or is not detectable.

In examining values for SST in the Daya Bay from AVHRR images, care must be taken to account for the thermal bias caused by land and by the chain of islands located in the central portion of the bay, especially for the Dapeng Cove since it is relatively small. The SST processing algorithm assigns a value of 0 for pixels that are out of range. Out-of-range values indicate infrared emissions from land or clouds. Because only cloud-free images were selected for this study, the 0 values represent land. Therefore, non-zero values represent SST. If, however, a pixel includes both water and land, the value will be biased. This bias occurs in the region of the central island chain and along the coastline.

The thermal plume is about 20 AVHRR pixels, but its size varies over time as shown in Fig. 4a. The plume is smallest in winter and largest in summer. It reaches about 40–80 pixels at points during June and August. At times during the winter (January and February), the plume is not visible on the images (see Fig. 4a, with pixel number "0"). The difference in temperature (delta $T$) between the plume and the non-plume areas is shown in Fig. 4b. The delta $T$ is in the range of 0.5–3.5 °C. When the plume does not show up in the images, the delta $T$ was recorded as "0", as shown in Fig. 4b. A histogram of the plume delta $T$ values is shown in Fig. 4c. There are 142 images with a delta $T$ in the range of 1.25–1.75 °C. Fig. 4d displays delta $T$ against area of the plume. Monthly variation of mean SST and maximal SST in the thermal plume is show in Fig. 4e. The highest SSTs appear in August and the lowest SSTs appear in February. Fig. 4f shows the difference of mean SST between daytime and nighttime in the thermal plume.

### 3.3. Survey measurements

Water temperature and Chl-$a$ are the highest at station 4 in the entire Daya Bay (Fig. 5). The water column structure during summer is reflected in the surface and near-bottom properties along a vertical section. Fig. 6 displays water column structure along the transect A from stations 3 to 7 (Fig. 1b) in July 1998. During the summer, warmer (Fig. 6a) and less saline (Fig. 6b) on the surface and colder and more saline on the bottom indicates the water column is strongly stratified.

Temperature and salinity at station 4, which is closest to DNPS, over the annual cycle from January 1998 to January

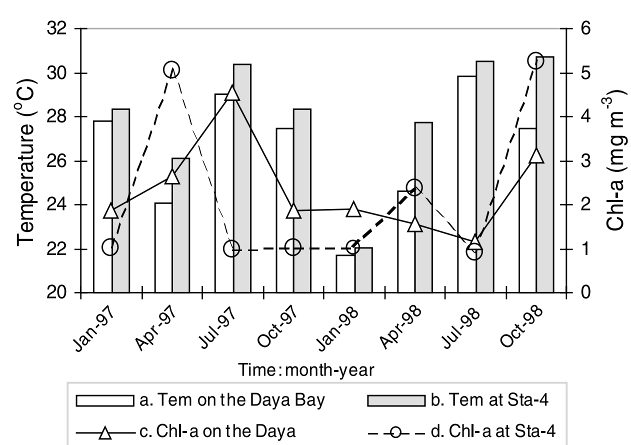


Fig. 5. Ship survey measurements of surface water temperature and Chl-$a$ at twelve stations (see Fig. 1b) in the Daya Bay. During January 1997 to October 1998: (a) Average temperature in the Daya Bay; (b) Temperature at station 4; (c) Average Chl $a$ in the Daya Bay; (d) Chl $a$ at station 4.

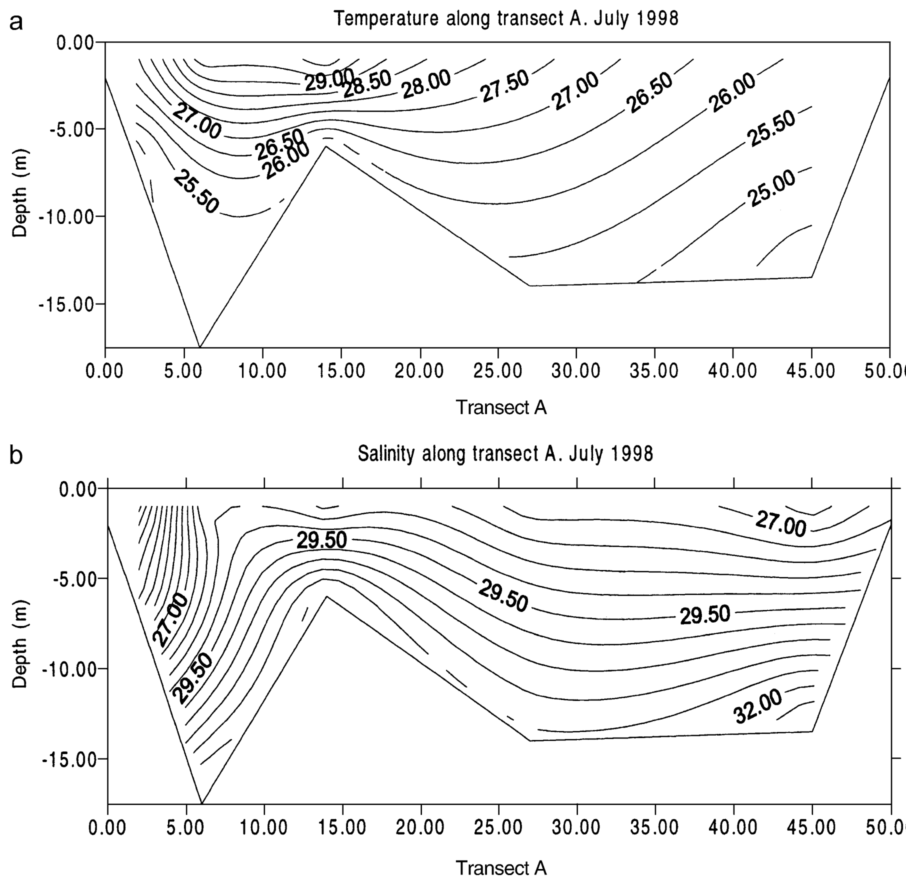


Fig. 6. Survey measurements along transect A (between stations 3 and 7, in Fig. 1b) in July 1998. (a) Temperature; (b) salinity.

1999 are shown in Fig. 7. The seasonal stratification of waters in this area is shown by the difference between surface and bottom water temperature and salinity. These differences are greatest in July 1998, with a temperature of 29.8 °C on the surface (a in Fig. 7) and 25.2 °C on the bottom (b in Fig. 7) on 19 July, and with a salinity of 28.2 on the surface and 32.4 on the bottom. The difference between surface and bottom are the smallest in January. For example, on 14 January 1999, temperatures are the same (18.4 °C) on surface and bottom (see a and b on Fig. 7), salinity is 32 on the surface and 31.8 on the bottom (see c and d on Fig. 7).

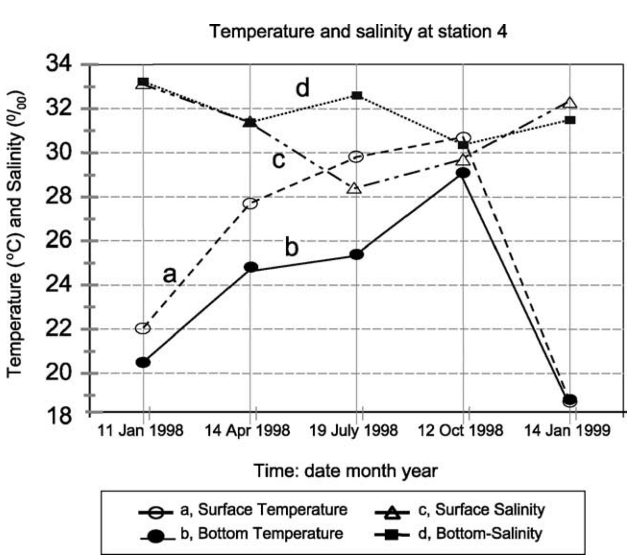


Fig. 7. Temperature and salinity at station 4 for surface and bottom waters during a 1-year period (January 1998 to January 1999).

## 4. Discussion

### *4.1. Water discharge from DNPS and satellite observation*

Before the operation of the DNPS, a numerical model predicted that the power station could affect the region 4 km from the power station to Dalakok (D on Fig. 1b) with a temperature change of 2 °C (Zhang, Guo, & Liu, 1984). Previous data showed that the annual variation of the water temperature was 16.85–31.60 °C before operation of DNPS (1990). It was 17–35 °C after operation began in 1994 (Huang et al., 1998). In the water 300–400 m away from DNPS, the highest surface temperature was 36 °C in summer and 32.40 °C in fall (Huang et al., 1998). This study shows the spatial and temporal distribution of water temperature from the warm water discharge of the power station. SST values extracted from AVHRR data show that the delta $T$ ranged from 1 to 3 °C over many square kilometers. The results clearly illustrate the seasonal pattern of the thermal plume in Daya Bay. During the winter months, the plume is confined to within a few kilometers of the nuclear power plant, but during the summer months the plume extends southeast from the power plant.

Huang, Cracknell, and Vaughan (1993) applied AVHRR images to obtain synoptic patterns of river plume off the west coast of Ireland. They reported that the plume frequents the mid-western coastal water north of the River Shannon estuary with a length of the order of 100 km and an area of about 100 $km^2$. Davies and Mofor (1993) applied Airborn Thematic Mapper (ATM) data on cooling water discharged from a coastal power station. Chuang & Tseng (1998) found good agreement between the ground truth temperature and satellite-derived SST for thermal plume of Hsinta power plant. For studying the thermal effluent from a large coal-fired electric generating facility, located on Mt. Hope Bay in the Narragansett Bay (Rhode Island, USA), Mustard, Carney, and Sen (1999) used a composite of 14 thermal infrared satellite images (Landsat TM Band 6) with a spatial resolution of 120 m to examine seasonal trends of surface temperature in the Narragansett Bay estuary. The present study applies AVHRR data to study the monthly variation of thermal plume from power station in a relatively small bay, such as Daya Bay. Satellite SST biases vary from area to area, and from time to time; SST data may have more biases for shallow water and coastal areas; the image coverage is negatively influenced by cloud. This study shows that the coverage of AVHRR data is good in late summer, fall and winter 1998 (Fig. 2).

We do not have NOAA SST data of $1.1 \times 1.1$ km resolution for the Daya Bay before 1994, prior to construction and operation of the power plant because of no satellite data receiving station; therefore we considered examining the Pathfinder AVHRR dataset for images prior to 1994, while these global coverage images have only 9 km resolution. We processed images of 9-km resolution for July and August 1998, when the 1-km images show the thermal plume clearly. However these SST images of 9 km resolution do not reveal thermal plume in Daya Bay. This study shows the feasibility of characterizing the thermal plume of DNPS using 1 km AVHRR satellite images.

### *4.2. Vertical mixing in winter and water stratification in summer*

The large seasonal difference in the thermal plume may be related to several processes. In summer, more cooling water is needed for the cooling system due to the high temperature water around the power station. An increase in the demand for electric power for air conditioning may require increased power output and thus an increase in cooling water discharge during the summer months. In this area, the northeast monsoon is strong in winter, while the weaker southwest monsoon is dominant in summer (Tang & Ni, 1996). During the winter, waters are vertically mixed in Daya Bay under the influence of the northeast monsoon (Zhan et al., 1990). This may be one of the reasons why the DNPS thermal plume is localized to within a few kilometers around the plant or cannot be detected by AVHRR during winter (Figs. 3a,g,h and 4).

In spring, sea surface temperatures increase, but vertical mixing is still important. The thermal plume starts to spread southeastward in late May. This increase in the size of the plume correlates with water stratification, which starts in late May (Li, Zeng, Xu, & Zhang, 1990; Zhan et al., 1990). Water stratification increases in June. In July, the temperature difference between the surface and bottom is more than 4 °C, and the salinity difference is more than 3 ‰ (Fig. 6b). Fresh water input diminishes the surface salinity, and water of lower temperature and high salinity intrudes into the bay along the bottom from the South China Sea (Ji & Huang, 1990). When the temperature difference between surface and bottom waters was 1 °C, the salinity difference between surface and bottom waters was more than 1 ‰ (Li, Zeng et al., 1990). During summer, the stratified waters confine the warm thermal plume in the upper few meters of the water column. The discharge of the warm water further increases the surface water temperature, which enhances stratification (Fig. 3c,e). It resulted the difference between mean SST and maximal SST in the thermal plume. This difference is larger in winter than in summer (Fig. 4e). The location of maximal SST is near the power station. This study also shows that SST is higher in daytime than in nighttime for the thermal plume during whole year around (Fig. 4f); it may indicate a diurnal warming of the water surface. Finally, the heat flux from the sea to the atmosphere is likely to be greater in winter than in summer. In Fig. 4d, the larger area of the plume with small delta $T$ may indicate stratification in summer; the small area with large delta $T$ may indicate mixing of the water column. In addition, the stronger northeast monsoon in winter increases vertical mixing, causing the small size of the plume in winter.

The distribution of the thermal discharge may be influenced by residual and tidal currents, and by water circulation as well. Dapeng Cove is a weak tidal cove (Xu, 1989). The tide speed is about 10 cm $s^{-1}$, and the average tidal range is smaller than 0.2 m. The tide in Daya Bay is a semidiurnal tide. The seasonal variation is more obvious and bigger than the daily variation of the plume affected by tidal current.

### *4.3. Environmental impact*

Studies on the environmental impact of warm water discharge have been undertaken for many power plants. For example, in the effluent zone of a coal-fired thermal power plant no phytoplankton existed during a 1-year study period (Srivastava, Ambasht, Kumar, & Shardendu, 1993). Briand (1975) reported that thermal discharge increased primary productivity in the water if environmental temperature was low or the delta-T was small. In Tampa Bay (Florida, USA), the number of fish species was consistently and significantly lower at warm sites near a power plant than at more distant, cooler areas (Henningsen, 1985). At least 20 species appeared to avoid the discharge area. With a 1–3 °C change of temperature, the discharge plume from DNPS may also result in some ecological changes in the lower portion of Daya Bay, particularly in Dapeng Cove.

Some surveys were conducted in the Daya Bay in 1991, before the operation of the DNPS. It showed that the water temperature in the surface (1 m below the surface) in the Dapen Cove was 17.53 °C in winter (January), 19.57 °C in spring (April), 30.66 °C in summer (July), and 17.53 °C in autumn (October) (Huang et al., 1998). Comparing these survey data obtained in 1991 with our data obtained in 1998, it could be observed that water temperature increased in the Dapeng Cove (Fig. 4e) after the operation of the DNPS. Our results show a difference of Chl *a* concentration among station 4 and the whole bay (Fig. 5), which maybe resulted from the warm discharge. The increase in water temperature can also favor the growth of some marine species relative to others.

In many cases, it is necessary to add chemicals to seawater cooling systems to control biofouling, scale deposits, or corrosion. These chemicals are dispersed in the discharge plume (Brook & Barker, 1972). More investigations are needed to determine if such chemicals have biological effects near the DNPS. The entrapment of organisms into the pumps and pipes of the cooling system can also be lethal. The AVHRR images provide a basis to design field studies on these ecological effects by showing the extent of the plume and the times of year with the most extreme conditions. The influence of the thermal plume on phytoplankton growth should also be further investigated.

## 5. Conclusion

SST images were processed and evaluated for the period November 1997 through June 1999. Seasonal variations in the thermal plume emanating from the DNPS were characterized. Estimates were made of the thermal contrast between the plume and the ambient waters. These show a temperature increase of 1–3 °C associated with the discharge of cooling water from DNPS. The size of the region of elevated SST was determined from the images. During the winter months, the plume is limited to a rather small area in the western side of the power station, whereas in summer it extends over 40–100 $km^2$ to the southeastern part of the bay. Shipboard measurements of water column showed the important role of stratification in Daya Bay. We attribute the seasonal difference in the size of the plume to mixing of the water column during the winter months, with the high temperature cooling water dispersed through the water column. In summer, however, the waters are stratified with warmer, less saline seawater at the surface. The thermal plume is confined to the surface layer where it tends to spread along the southwest portion of Daya Bay.

The present study is the first time attempt to apply AVHRR data for studying on thermal plume from power station on a relatively small bay, such as the Daya Bay. This study shows how satellite remote sensing can provide information about the distribution and seasonal variation in thermal plumes from power plants that discharge cooling waters in coastal areas. Studies of coastal phenomena using individual 1 km images can reveal features and processes that are obscured when spatial and temporal composite images are used; SST images with $9 \times 9$ km resolution may smear out important features for this small bay. AVHRR SST is higher in daytime than in nighttime in the bay during the whole year; it may indicate a diurnal warming on the surface water. New insights can be gained into the extent of these plumes and the areas that they affect. Combining satellite remote sensing with shipboard monitoring studies can provide reliability checks in the assessment of the ecological consequences of thermal plume water.

## Acknowledgements

Dr. DanLing Tang's work was supported by funding from the Croucher Foundation of Hong Kong, through a grant to Professor G.W. Heinke in 1998, and a fund from the National Space Development Agency of Japan (NASDA) through a grant to the Asian I-Lac Project at Tohoku University. This work was also partly supported by funding from the Chinese Academy of Science (No. KZ95T-04-04-04). We thank Mr. W. Huang of the Center for Coastal and Atmospheric Research, The Hong Kong University of Science and Technology, for his assistance in making the AVHRR data available.

## References

Briand, F. J. (1975). Effects of power-plant cooling systems on marine phytoplankton. *Marine Biology*, *33*, 135–146.

Brook, A. J., & Barker, A. L. (1972). Chlorination at power plants: impact on phytoplankton productivity. *Science*, *176*, 1414–1415.

Chen, C., Shi, P., & Mao, Q. W. (1996). Satellite remote sensing survey of chlorophyll concentration of surface waters in Daya Bay. In R. L. Zuo (Ed.), *Sustainable utilization of oceanic bio-resources at Daya Bay* (pp. 56–59). Beijing: Science Press, in Chinese.

Chuang, H. -H., & Tseng, R. -S. (1998). Remote sensing of SST around the outfall of a power plant from LANDSAT and NOAA satellite. *Journal of Photogrammetry and Remote Sensing*, *3*(2), 17–45 (in Chinese).

Davies, P. A., & Mofor, L. A. (1993). Romote sensing observation and analyses of cooling water discharges from a coastal power station. *International Journal of Remote Sensing*, *14*(2), 253–273.

Han, W. Y. (1991). The carbon cycling of Daya Bay and Pearl River Estuary. Beijing, China: Science Press.

Henningsen, B. F. (1985). Effects of thermal effluents on the distribution, abundance, and fecundity of fish in Tampa Bay, Florida, including thermal tolerance studies involving laboratory and in situ caging. *Dis-*

*sertation Abstracts International part B: Science and Engineering*, *46* (6), 257.

Huang, W. G., Cracknell, A. P., & Vaughan, R. A. (1993). Satellite thermal observation of the River Shannon Plume. *Estuarine, Coastal and Shelf Science*, *36*(3), 207–219.

Huang, X., Zhu, Z., Xu, M., & Jing, Q. (1998). Variation of water temperature in the southwestern Daya Bay before and after the operation of Daya Bay Nuclear Power Plant. In J. Pen, & Z. Wang (Eds.), *Annual research reports, Marine Biology research station at Daya Bay* (pp. 102–112). Beijing, China: Science Publishing House, in Chinese.

Ji, W. D., & Huang, S. G. (1990). Relationship between nutrient variation in Daya Bay water column and hydrographical and biological factors. In Third Institute of Oceanography, SOA (Eds.), *Collections of Papers on Marine Ecology in the Daya Bay (II)* (pp. 123–132). Beijing, China: Ocean Publishing House, in Chinese.

Kahru, M. (1999). *Windows Image Manager*. CD ROM. Available at: http://spode.ucsd.edu/.

Kester, D. R., & Fox, M. F. (1993). Chemical and biological remote sensing of the South China Sea: satellite and in situ observations. In M. Fang & A. Liu (Eds.), *Proceeding of Environment'93-Symposium on Remote Sensing in Environmental Research and Global Change* (pp. 60–72, 135–139). The Commercial Press, Hong Kong.

Kester, D. R., Fox, M. F., Magnuson, A., & Andrews, J. E. (1996). Applications of AVHRR satellite remote sensing to surface temperatures in coastal waters. *EOS, Transactions, American Geophysical Union*, *76* (3), OS195.

Li, L., Zeng, G., Xu, J., & Zhang, B. (1990). Phenomena of cold water invasion into Daya Bay during summer 1987. In Third Institute of Oceanography, SOA (Eds.), *Collections of Papers on Marine Ecology in the Daya Bay (II)* (pp. 95–99). Beijing, China: Ocean Publishing House, in Chinese.

Li, L., Zhang, B., & Zeng, G. (1990). Currents of Daya Bay. In Third Institute of Oceanography, SOA (Eds.), *Collections of Papers on Marine Ecology in the Daya Bay (II)* (pp. 87–94). Beijing, China: Ocean Publishing House, in Chinese.

Li, T. F., Xu, B. Z., & Yi, J. C. (1990). *The information extract and application of the ocean satellite remote sensing* (pp. 103–108). Beijing: China Ocean Press, in Chinese.

McClain, E. P., Pichel, W. G., & Walton, C. C. (1985). Comparative performance of AVHRR based multichannel sea surface temperatures. *Journal Geophysical Research*, *90*, 11587–11601.

Mustard, J. F., Carney, M. A., & Sen, A. (1999). The use of satellite data to quantify thermal effluent impacts. *Estuarine, Coastal and Shelf Science*, *49*(4), 509–524.

Pan, J., & Cha, G. (1996). *Annual Research Reports (I), Marine Biology Research Station at Daya Bay.* Beijing, China: Science Publishing House (in Chinese).

Pan, J., & Wang, Z. (1998). Annual Research Reports (II), Marine Biology Research Station at Daya Bay. Beijing, China: Science Publishing House (in Chinese).

Srivastava, N. K., Ambasht, R. S., Kumar, R., & Shardendu, R. (1993). Effect of thermal power effluents on the community structure and primary production of phytoplankton. *Environment International*, *19*(1), 79–90.

Tang, D. L., Kawamura, H., & Luis, A. J. (2002). Short-term variability of phytoplankton blooms associated with a cold eddy on the North-western Arabian Sea. *Remote Sensing of Environment*, *81*(1), 82–89.

Tang, D. L., Kester, D. R., Ni, I. -H., Kawamura, H., & Hong, H. (2002). Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements. *Remote Sensing of Environment*, *83*(3), 457–471.

Tang, D. L., & Ni, I. -H. (1996). Remote sensing of Hong Kong waters: spatial and temporal changes of sea surface temperature. *Acta Oceanographic Taiwanica*, *35*(2), 173–186.

Tso, M. W., & Li, C. C. (1992). Terrestrial gamma radiation dose in Hong Kong. *Health Physics*, *62*(1), 77–88.

Wen, W. Y., He, Y. Q., & Zhen, Q. H. (1992). Environmental study of Daya Bay. *Tropical Ocean*, *11*(2), 25–30 (in Chinese).

Xu, G. Z. (1989). *Environments and resources of Daya Bay* (pp. 10–16). HeFei, China: Anhu Science Publishing House, in Chinese.

Zang, M. C. (1993). Nuclear power programs in China. *Atomwirtschaft-Atometechnik*, *38*(6), 419–420 (in German).

Zeng, W. X. (1994). Guangdong Daya Bay nuclear power station project. *Transactions of the American Nuclear Society*, *70*(1), 205–210.

Zhan, B., Zeng, G., & Li, L. (1990). Temperature and salinity of Daya Bay. In Third Institute of Oceanography, SOA (Eds.), *Collections of Papers on Marine Ecology in the Daya Bay (II)* (pp. 67–74). Beijing, China: Ocean Publishing House, in Chinese.

Zhang, W., Guo, H., & Liu, L. (1984). *Marine chemistry* (pp. 54–55). Shanghi, China: Shanghi Science and Technology Publishing House.

Zheng, Q., He, Y., & Zhang, G. (1998). Impact on the changes of chemical composition of seawater from waste water discharge in Daya Bay. In J. Wang, & Z. Wang (Eds.), *Annual Research Reports, Marine Biology Research Station at Daya Bay (II)* (pp. 129–134). Beijing, China: Science Publishing House, in Chinese.