ABSTRACT

Daya Bay is a shallow semi-enclosed bay in the northern South China Sea. The present study analyzed variations of water temperature in this bay during the past twenty years using satellite remote sensing and in situ observations during 1985-2005. Results showed that AVHRR sea surface temperature (SST) has increased, while the Daya Bay nuclear power station began operation in 1994. Thermal plume distribution was analyzed through AVHRR monthly images in 2005. In situ observations for water surface temperature (WST) also showed increase trend during 1970-2005. Variations of water temperature in Daya Bay may be connected with climatic perturbations and increasing human activities including thermal discharge from nuclear power stations and the rapid economic development around Daya Bay.

INTRODUCTION

Sea surface temperature (SST) is a primary tracer of physical coastal dynamics and closely related to near-shore ecosystem functions. It provides important baseline information for understanding coastal processes (Fisher and Mustard, 2004). In some cases, change of water temperature can lead to changes in species diversity, patterns of energy flow and, in the most extreme cases, alternations of entire ecosystems (MacLeod et al., 2005).
Daya Bay is located in the northern South China Sea (SCS; Fig. 1A). It was one of the major aquaculture areas in the Guangdong province because of its excellent water quality and rich biological resources (Xu, 1989). Since the late 1980s, economic developments in industries, aquaculture and agriculture in the area have rapidly expanded. For example, the first large-capacity commercial nuclear power unit in China, Daya Bay nuclear power station (DNPS), began operation in early 1994. Near to the DNPS, another nuclear power station, Lingao nuclear power station (LNPS) has also been in operation since 2003 (www.cgnpc.com.cn). The two nuclear power stations have been discharging thermal water to Daya Bay continuously since their operation (www.cgnpc.com.cn). Other industries such as petrochemical, printing, harbors and tourism are also present (Fig. 1B). Along with these activities, the water quality status of Daya Bay has deteriorated (Zhou and Maskaoui, 2003) and the occurrences of harmful algal bloom (HAB) in the bay area have been more frequent (Song et al., 2004; Wang et al., 2006). The environmental condition in Daya Bay has changed.

With the development of space technology, more remote sensing data are available for monitoring and studying the marine environment. Satellite remote sensing can complement in situ observation on providing additional information of the spatial and temporal variation (Wynne et al., 2005; Tang et al., 2003, 2004; Zhao and Tang, 2007). Compared to the high costs of monitoring using traditional methods, satellite remote sensing also provides an economy method. Among various satellite sensors, Advanced Very High Resolution Radiometer (AVHRR) onboard National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites has a long-term record of SST for more than twenty years. It offers large benefits to investigate sea surface status. Previous study on Daya Bay has observed the seasonal distribution of SST through daily AVHRR images (Tang et al., 2003). Landsat Thematic Mapper (TM) satellite remote sensing was also applied to the bay (Chen et al., 2003).
In Figure 1, the circles indicate the location of nuclear power stations (DNPS and LNPS) at the mouth of Dapeng Cove (DC). Small boxes with a shadow show Petrochemicals Co. Ltd. in the northwest of Daya Bay and their pollutant effluent in the east of the bay. Box “a” indicated by interrupted lines shows the sample area where the AVHRR SST data was derived. The black dots show the 12 survey stations.

Daya Bay has experienced long time development and its ecological and economic landscapes have changed profoundly, it provides a unique opportunity to study the response of marine environment to natural variability and anthropologic influence in bay area. In order to get a better understanding of the marine environmental changes in Daya Bay, we have attempted to analyze the temporal and spatial changes of water temperature using long-term satellite remote sensing and in situ data. Results of this work would help assess response of marine environment to human activities and natural change in bay area.

**RESEARCH AREA AND DATA**

**Research area**

Daya Bay is a shallow semi-enclosed bay located at 22°30′-22°50′N, 114°30′-114°50′E, in the northern South China Sea (SCS; Fig. 1). It covers an area of about 600 km² with an irregular coastline and more than 50 islands inside the bay area. The deepest site is 21m near the bay mouth and the average water depth is 11m. No major rivers discharge into Daya Bay, and water exchange inside the bay and the SCS is mainly through the bay mouth (Xu, 1989). The tidal current in Daya Bay is dominated by a semidiurnal irregular tide with an average tidal day of 24.7h. As Daya Bay locates in a subtropical region, the averaged background water temperature in the coastal water is 29.3°C in summer (July to September) and 17.3°C in winter (December to February; Zeng et al., 2002).

**Satellite remote sensing data**

The Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA's Polar Orbiting Environmental Satellites (POES) is a broad-band, four or five channel scanner, sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum. (http://edcns17.cr.usgs.gov/1KM/avhrr_sensor.html). AVHRR provides Sea Surface Temperature (SST) information continuously for a long time period (1978 - present) and at large scale that had previously been impossible to achieve by ship observation.

In this study, a total of 7614 NOAA-AVHRR SST data with ~4 km spatial resolution from January 1985 to December 2005 were obtained from NASA Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO-DAAC) PATHFINDER database (http://podaac.jpl.nasa.gov/index.html). ASCII format data were derived from those AVHRR SST data.
for the sample area of box a (22.50-22.83°N, 114.50-114.82°E; box a, Fig. 1B) through MATLAB 7.0.1 software package. Those ASCII format SST data were then processed to yearly and monthly mean values for the period 1985-2005. The monthly SST data were also processed to monthly SST anomaly (SSTA) for the same period. For a better understanding of the SST distribution, we processed SST data sets with ~1 km spatial resolution during 2005 to monthly average images through MATLAB 7.0.1 software package. Both ~1 and ~4 km spatial resolution SST data were night products.

In situ data

The South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences, has the Marine Biological Research Station (MBRS, Fig. 1B) in Dapeng Cove (DC, Fig. 1B), has made a series of surveys over twelve stations in Daya Bay since 1982 (black dots, Fig. 1B). These surveys were conducted in spring (April), summer (July), fall (October), and winter (January) every year on seawater temperature, Chl-a, nutrient, pH, biomass of the biota, etc (www.cern.ac.cn:8080/index.jsp). Our “Remote Sensing and Marine Ecology/Environment Group” also made in situ sea water temperature data during 2003-2005 for Daya Bay. Those data together with Daya Bay environment research reports (South China Sea Institute of Oceanology, Chinese Academy of Sciences) were important database for the present study. A total of 1845 in situ WST data from January 1970 to November 2005 were processed to annual mean values and analyzed in this study.

RESULTS

Annual increase of SST

Yearly mean SST during the period 1985-2005 varied from 18.35 (1988) to 20.87°C (2005; Fig. 2A). Linear regression analysis for SST showed an ascending trend. It was noticed that there
was a great increase of SST in 2005 (circle, Fig. 2A). The total number of annual SST data ranged from 357 to 366, covering each month throughout the year (Fig. 2B).

**Seasonal variation of SST**

To investigate the changes of SST in Daya Bay over the past two decades, we processed ~4 km spatial resolution SST data to time series of monthly mean SST from 1985 to 2005. The lowest SST was 11.5ºC (February 1992) and the peak SST was 26.4ºC (July 2005). For most of years, there was only one peak SST with its value higher than 26ºC. But it was noticed that SSTs in July, August, and October 2005 were higher than 26ºC.


Monthly SST variation from 1985 to 2005 showed the increase of water temperature in each month and the seasonal extension of higher SST. Before 1994, the peak SST (~26ºC) appeared only in one month and the lowest SST was ~12ºC in February 1992; while after 1994, the peak SST extended to two months (July-August 2005; black arrow, Fig. 4) and the lowest SST increased to ~14ºC in February 2000. Higher SST season (SST≥22ºC) extended from three months (July-September) in 1985 to five months (July-November) in 2005. It was noticed that there was a remarkable increase of SST in the Fall (September to November) 1994, when the DNPS began operation.

**Thermal plume distribution**

The ~1 km spatial resolution SST data during 2005 were processed to images to show the spatial distribution of thermal plume from the two nuclear power stations (NPS; including DNPS and LNPS). Four images of monthly mean SST in winter (January), spring (April), summer (July), and fall (October) were displayed in Figure 3. For a better display, color bars with different scales were used to show SST in different seasons.

Thermal plume with 1-2ºC higher than adjacent waters in the bay was observed in the satellite images (black arrows, Fig. 3). It localized near to the output of NPS in January (Fig. 3A), spread to the northeast of Daya Bay in April (Fig. 3B), extended to the southeast of the bay in July (Fig. 3C), and reached to the northwest of the bay in October (Fig. 3D).
In situ water temperature observation

In this study, \textit{in situ} water surface temperature (WST) for a longer time period from 1970 to 2005 was investigated. Annual mean WST ranged from 21.6ºC (1986) to 26.6ºC (1999; Fig. 4A). The number of WST data for each year was displayed in Figure 4B. The WSTs in 1983, 1989, 1990 and 1995 were excluded from the linear regression analysis, because WST in those years was sampled in limited months. In 1989, WST was sampled in summer, and in 1983, 1990 and 1995, WST was sampled in winter and spring (Fig. 4B). This was one of the reasons why higher or lower WST was displayed in those years.

DISCUSSION

Increase of water temperature in Daya Bay was observed through both satellite remote sensing and in situ observations, coinciding with increase of human activities, thermal discharge from nuclear power stations in the bay area, and the global warming.

Change of Environmental conditions

During the past fifty years (mid-1950s to mid-1990s), the global mean ocean temperature has increased by 0.31ºC, due to the combination of natural variability and anthropogenic effects (Levitus \textit{et al}., 2000). At the same time, the heat content of the world ocean has increased and the average rate of sea-level change obtained from tide gauges is $+1.8\pm0.3$ mm yr$^{-1}$, because of the increase of anthropogenic gases in Earth’s atmosphere (Levitus \textit{et al}., 2001; Nerem \textit{et al}., 2006). In Bohai Sea, China, which is a shallow semi-enclosed sea without power plant, surface water temperature increased 0.011ºC yr$^{-1}$ during 1960-1997 (Lin \textit{et al}., 2001). The present study also observed increase trend of SST in Daya Bay during 1985-1993, before NPS operation, indicating its response to the global warming.

Besides the influence of natural variability, anthropogenic effects are also important. Daya Bay has experienced remarkable change over the past two decades, especially after the DNPS
operation in 1994. Aquacultural, industrial and agricultural activities expanded rapidly in the area, as well as developments in tourism and the construction of harbors and highway. Aquaculture increased dramatically from 1,000 pens in 1988 to 20,500 pens in 2004, and permanent resident population around Daya Bay doubled from 1,217,600 in 1979 to 2,359,000 in 1997 with additional 1,000,000-1,200,000 nonresidents (www.huizhou.gov.cn/). The rapid urbanization around Daya Bay would make contribution to the elevation of water temperature in this area (Chen et al., 2006).

Thermal discharge from nuclear power station (NPS)

The DNPS and LNPS discharge thermal water with 8-10°C above adjacent to Daya Bay through one pipe at a rate of 190 m³ s⁻¹ (Tang et al., 2003). This thermal plume spreads several square kilometers away from the NPS (Fig. 3). A comparison near the DNPS in 1993 and 1998 showed in situ WST increased by 0.77°C (Peng et al., 2001). The present study observed a rapid increase of SST in Daya Bay higher than that in Bohai Sea (0.011°C y⁻¹ during 1960-1997), which is also a semi-enclosed bay but there is no power plant (Lin et al., 2001). This may reveal the influence of thermal discharge from the power stations to marine environment.

In this study, more investigations have been conducted for monthly SST and SSTA from 1985 to 2005 to understand the variation of water temperature in Daya Bay (Figs. 3 and 4). During 1985-1993 before the NPS operation, SSTA may indicate the response of water temperature to natural variability. In addition, the slope comparison between the two periods (1985-1993 and 1994-2005) also showed more rapid increase of water temperature after the NPS operation (Fig. 3B, C). Our previous study observed seasonal distribution of SST through daily AVHRR satellite images (Tang et al., 2003), the present study analyzed monthly AVHRR images (Fig. 3). Both studies observed high-temperature water near to the NPS and its extension in the bay area.

Daya Bay is a semi-enclosed bay, where water circulation with the SCS is rather slow (Xu, 1989), therefore, the increase of water temperature in the bay area was higher than that in the
coast water. Furthermore, bays generally had a more amplified response to change than more open water bodies (Mustard et al., 1999; Fox et al., 2000). The DNPS has been discharging warm water to the bay for more than 10 years, and hence exacerbated water temperature elevation in the bay area.

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