Changes of Water Temperature and Harmful Algal Bloom in the Daya Bay in the Northern South China Sea

YU Jing [1, 2, 3], TANG Danling [1, 2], WANG Sufen [1, 2], LIAN Jiansheng [1], WANG Youshao [4]

1. *Remote Sensing and Marine Ecology / Environment Group (RSMEE), Key Laboratory of Tropical Marine Environmental Dynamics (LED), South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou* 510301*, Guangdong, China; Lingzistdl@*126*.com*

2. *Graduate School of the Chinese Academy of Sciences, Beijing* 100039*, China;*

3. South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou 510300*, Guangdong, China;*

4. *LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou* 510301*, Guangdong, China;*

Abstract : Economic development around the Daya Bay, China has profoundly affected the marine environment in the bay area in recent years, particularly since the operation of Daya Bay Nuclear Power Station (DNPS) in 1994. This study analyzed the changes of water temperature and harmful algal blooms (HABs) for two periods: 1983-1993 and 1994-2004, using *in situ* and satellite data. Results showed that yearly mean surface water temperature (SWT) and Chl-*a* concentration (Chl-*a*) increased by 1.1 ℃ and 1.9 mg/m^3, respectively, after 1994. The monthly occurrence of HAB was found to have increased also. HABs appeared only in spring and autumn before 1994, but occurred all the year round after 1994. SWT, Chl-*a* and HABs all increased significantly in May. Those changes were associated with environmental changes in this area, such as thermal discharge from the DNPS and enhancement of eutrophication from human activities around the Daya Bay.

Keywords: water temperature; Harmful Algal Bloom; Chlorophyll *a*; nuclear power station; Daya Bay, China

Introduction

Economic development around the Daya Bay has expanded rapidly since the operation of the first large-capacity commercial nuclear power unit in China (Daya Bay Nuclear Power Station, DNPS) in 1994 (Fig.1A, B). The second nuclear power station (Ling Ao Nuclear Power Station, LNPS) near DNPS also started its first-stage operation in early 2003 (Fig.1A). Other industries such as petrochemical, plastic, printing and harbors are also present. Cage aquaculture along the coastal waters in the bay increased dramatically in recent years and reached 20500 cages in 2004 (http://www.huizhou.gov.cn/).

Investigation in the Daya Bay showed the high temperature effluent from the power station was one

Received on November 13, 2006

of the main artificial impacts. Increase of water temperature and nutrient supply from land-sources may stimulate Harmful Algal Blooms (HABs) [1-4] (Fig.1C, HAB photo was available from: http://www.gdofa.gov.cn/asp/home/index.asp). HABs are regarded as a serious problem throughout the world and have also caused considerable economic loss in the Daya Bay. For example, a HAB caused fish mortality of about 75 tons in March 1983. Another two HABs occurring in August 2000 and August 2003 resulted in losses of about US $370,000 and US $41,000, respectively (http://www.china-hab.cn).

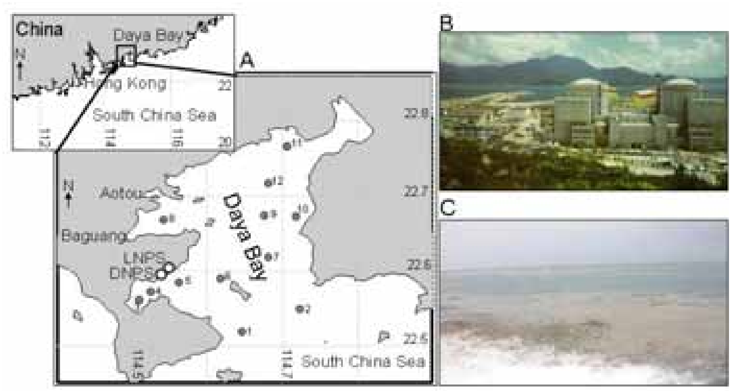

Fig.1 (A) Daya Bay map with Daya Bay Nuclear Power Station (DNPS) and Ling Ao Nuclear Power Station (LNPS) in Dapeng Cove (DC).

The small box indicates the location of Daya Bay in the South China Sea.

Twelve survey stations (indicated by shaded circles) are shown in the Daya Bay.

(B) Photo of DNPS. (C) A Harmful Algal Bloom in the Daya Bay in June 2004.

Daya Bay is an ideal area in which to study and assess impacts of thermal discharge and environmental changes on algal blooms because of its semi-closed shape, suitable size and long-time observation data. It has already received much attention for its environmental changes [5-9]. In this study, we have interest in: What are changes in the surface water temperature (SWT) after the DNPS operation in 1994? How do the changes of water temperature affect Chlorophyll *a* concentration (Chl-*a*) and HAB frequency? In order to answer these questions, historical observations (1970-2005) and satellite remote sensing data (1997-2004) were used to analyze the changes of SWT, Chl-*a* and HAB frequency after the DNPS operation.

1 Research area and methods

1.1 Research area

Daya Bay is located at 22.5ºN-22.9º N, 114.5ºE-114.9º E, covering an area of about 550 km^2 with an irregular coastline and more than 50 islands inside the bay area (Fig.1A). It is rather shallow, with a maximum depth of 21 m and a mean depth of 11 m. Located in a sub-tropical region, Daya Bay's annual mean air temperature is about 22 °C, with the coldest months in January-February (15 °C) and the hottest months in July-August (28 °C). As a semi-enclosed bay, currents in the Daya Bay are dominated by tides, and the water circulation with the SCS is fairly slow. No major rivers discharge into the Daya Bay [6, 8].

1.2 In situ data collection and analysis

All available data of SWT, Chl-*a* and HABs were collected from relevant references [7, 10-13] and Daya Bay environmental research reports over more than 30 years (1970-2005). Our institute, South China Sea Institute of Oceanology (SCSIO), has also made a series of research surveys over 12 stations in the Daya Bay since 1982 (Fig.1A). These surveys have been conducted in spring (April), summer (July), fall (October) and winter (January) every year, and include measurements of seawater temperature, salinity, pH, biomass of the biota and etc [8].

In this study, we have collected a total of 3188 data from January 1970 to June 2005, including SWT (2331 data during 1970-2005), Chl-*a* (790 data during 1984-2005) and HAB frequency (67 data during 1983-2004). All these data were processed to yield monthly mean values for the entire Day Bay, to compare between two periods: before and after the DNPS operation in 1994.

1.3 Satellite SeaWiFS data

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project provides quantitative data on global ocean bio-optical properties through satellite remote sensing (http://oceancolor.gsfc.nasa.gov/SeaWiFS/). We processed monthly average SeaWiFS-derived Chl-*a* data (1997-2004) with ~1 km spatial resolution for the Daya Bay using the Ocean Color 4-band algorithm [14] through the SeaWiFS Data Analysis System [15] (SeaDAS). Color bars with different scales were used to show Chl-*a* concentrations and distribution in different seasons.

2 Results

2.1 Increase of surface water temperature (SWT)

Comparison for monthly data between the two periods (before and after 1994) showed an increase in SWT (Fig.2A). Before 1994, the lowest SWT was 16.5 °C (January) and the highest SWT was 29.0 °C (July); after 1994, the lowest SWT increased to 17.2 °C (March) and the highest SWT reached 29.7 °C (July and August). The yearly mean SWT was 23.3 and 24.4 °C before and after 1994, respectively, with an increase of 1.1 °C (Fig.2A).

2.2 Changes of Chl-*a* concentration

Chl-*a* concentration increased in every month after 1994 (Fig.2B). Before 1994, the highest Chl-*a* concentration was 2.9 mg/m^3 (June) and the lowest was 1.4 mg/m^3 (January). After 1994, the highest Chl-*a* concentration was found to be 7.2 mg/m^3 (May) and the lowest was 2.3 mg/m^3 (February). The yearly mean Chl-*a* concentration increased from 1.9 mg/m^3 before 1994 to 3.8 mg/m^3 after 1994 with an elevation of 1.9 mg/m^3 (Fig.2B).

Satellite ocean color images derived from SeaWiFS showed the spatial distribution of Chl-*a* in the Daya Bay in January, March, July and October during 1997-2004 (Fig.3). For a better display, color bars with different scales were used to show Chl-*a* in different seasons. High Chl-*a* concentrations were observed in the waters near DNPS in July (indicated by red arrow in Fig.3C), as well as in the coastal waters northwest of Daya Bay (indicated by red circles in Fig. 3) all the year round.

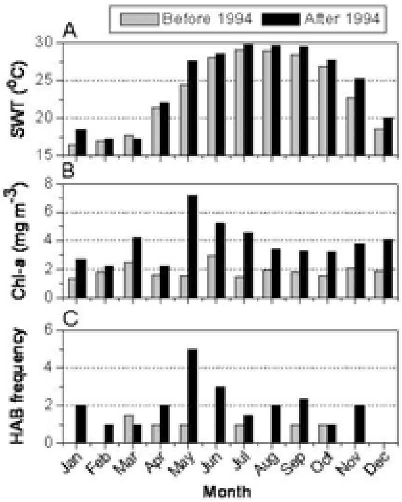

Fig.2 Comparison of (A) surface water temperature (SWT), (B) Chlorophyll *a* (Chl-*a*) and (C) Harmful Algal Bloom (HAB) frequency between two periods: before and after 1994.

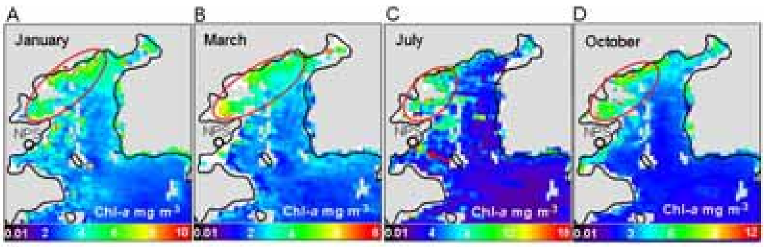

Fig.3 SeaWiFS-derived monthly average Chl-*a* images with ~1km spatial resolution during 1997-2004. (A) January; (B) March; (C) July; (D) October

The black circle indicates the location of nuclear power station (NPS) including DNPS and LNPS.

Red circles indicate cage aquaculture waters in the northwest of Daya Bay.

Red arrow indicates waters with high Chl-*a* concentrations near to the NPS.

2.3 Seasonal change of HAB frequency

Comparison of HAB seasonality between the two periods (before and after 1994) showed HABs lasted for longer seasons after 1994 (Fig.2C). During 1983-1993, HABs appeared mainly in spring and autumn months; while during 1994-2004, HABs occurred all the year round with the largest increase in May. The occurrence frequency of HAB also increased in most of the months after 1994 (Fig.2C).

2.4 Analysis of water temperature, Chl-a and HAB frequency

In order to understand the relation between the changes of SWT, Chl-*a* and HAB frequency, we compared the difference in monthly SWT (Delta SWT) and Chl-*a* concentration (Delta Chl-*a*) between the two periods: before and after 1994 when DNPS began operation (Fig.4).

Delta SWT (change of monthly mean SWT before and after 1994) ranged from -0.5 ℃ (March) to 3.2 ℃ (May), indicating SWT increased in each month except in March (Fig.4A). Delta SWT was relatively high in winter and spring months (November to May except March) compared to summer months (June to September). Delta Chl-*a* (change of monthly mean Chl-*a* before and after 1994) increased during the DNPS operation, with the largest value of 4.5 mg/m^3 (May) and the smallest value of 0.1 mg/m^3 (April) (Fig.4A). As was shown in (Fig.4A), Delta SWT and Delta Chl-*a* displayed a similar trend in most of the months. Delta HAB (change of monthly mean HAB frequency before and after 1994) ranged from -0.5 (March) to 4 (May) (Fig.4B). Delta SWT showed some positive correlation with Delta HAB (Fig.4B) and Delta Chl-*a* (Fig. 4A). The peak and lowest values of Delta SWT and Delta HAB occurred in the same months (Fig.4).

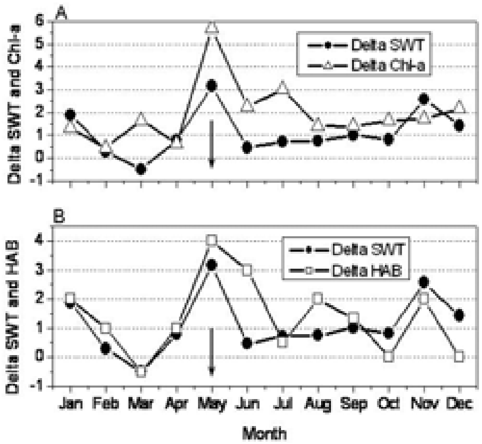

Fig.4 Monthly variations of change in the surface water temperature before and after 1994 (Delta SWT), change in Chl-*a* before and after 1994 (Delta Chl-*a*) and change in HAB frequency before and after 1994 (Delta HAB).

(A) Delta SWT and Delta Chl-*a*; (B) Delta SWT and Delta HAB.

Arrows indicate the month when peak values appeared.

3 Discussion

3.1 Temperature increase and thermal discharge

Our previous study observed the SWT difference between the plume and non-plume area was about

1.5 ℃ in winter and 1 ℃ in summer and fall in the Daya Bay [9]. An early comparison near DNPS between 1991 and 1994 showed that SWT increased by 0.3 ℃ [5]. The present study for a longer period from 1970 to 2005 observed the yearly mean SWT increased by 1.1 ℃ after DNPS operation in 1994 (Fig.2). Daya Bay is a semi-enclosed bay, so its water circulation with the South China Sea is rather slow [8]. And the bay generally has a more amplified response to environmental changes than open water bodies [16-17]. All of these may have contributed to the increases of SWT in the Daya Bay.

We found that changes of SWT (Delta SWT) were less in summer months (June to September) and more in winter months (November to February) (Fig.4), consistent with our previous study for 1998-1999 in the Daya Bay [9]. In summer, the water was stratified under the dominance of weaker southwest monsoon, impact of the high temperature water was limited to the upper layer of water near the discharge point. Therefore, for the entire bay area, the increase of SWT was found less in summer months. But for the area near the outlet of DNPS, the increase of SWT was more significant. During winter, the waters were vertically mixed under the influence of the strong northeast monsoon and SWT in the entire bay area decreased [8]. Therefore, the increase of SWT induced by the thermal discharge in the local waters was more significant.

3.2 Increase of Chl-*a* and HABs related with temperature and eutrophication

Temperature is one of the important environmental variables that affect the survival, growth and reproduction of aquatic organisms [3, 18]. In this study, we verified the close relation between water temperature and Chl-*a* (and HABs) in such a small bay as Daya Bay. Both of Delta SWT and Delta Chl-*a* (or Delta HAB) showed a positive correlation in most of the months (Fig.4), indicating that temperature may have stimulated the algal growth, and thus HAB occurences. Relevant study showed the water temperature increase from the power station would create conditions favorable for the algal growth [19]. In our satellite Chl-a images (Fig. 3C), waters with high Chl-*a* concentrations were observed near DNPS, indicating that the thermal discharge from the DNPS may help the algal growth.

Before 1990, the nutrient level in the Daya Bay was rather low [8]. But in the past decade, increasing cage aquaculture enhanced local eutrophication, particularly for the coastal waters northwest of Daya Bay (Fig. 5) (cage aquaculture data were from http://www.huizhou.gov.cn/). Total inorganic nitrogen (TIN=NO_3-N+NO_2-N+NH_4-N; mg/L) also enhanced from 0.021 (1986) to 0.068 mg/L (1999) and kept a relatively high level after 1999 (Fig.5). Satellite Chl-*a* images showed high Chl-*a* areas in the aquaculture waters (Fig.3), indicating the nutrient was partially from cage aquaculture. The nutrient situation in the Daya Bay has experienced a remarkable change in the past 2 decades: N/P ratio increased from 1.5 to 59.8 and the limiting nutrient factor has changed from N to P [7]. The nutrient status has changed from the low level in the 1980s to the middle or even eutrophicated level in some areas of the bay at present. Eutrophication has become an important factor contributing to the annual occurrences of HAB, and it is at least partially responsible for the increase in the frequency and areal extent of HABs.

It was noticed that SWT, Chl-*a* concentration and HAB frequency increased a lot in May after 1994 (Fig.4), indicating May may be a sensitive month for marine ecology and environment. More investigations and analysis are needed to understand it.

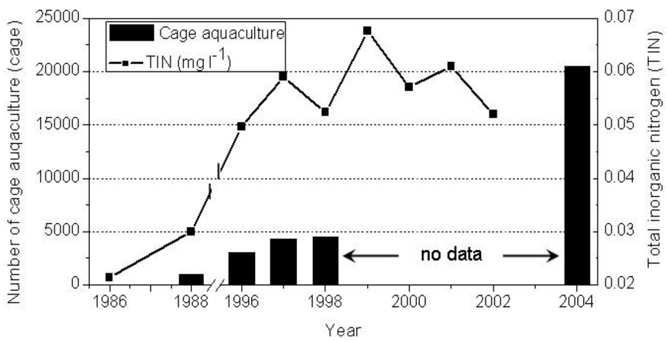

Fig.5 Variation of cage aquaculture and total inorganic nitrogen (TIN) in the Daya Bay from 1986 to 2004

4 Summary

This study analyzed historical observation data for 1970-2005 and satellite remote sensing images for 1997-2004.

(1) Surface water temperature and Chl-*a* concentration increased in the Daya Bay, partly because of the thermal discharge from the DNPS.

(2) HAB frequency increased remarkably after 1994, particularly in May, which was associated with the increasing of water temperature and eutrophication around the Daya Bay.

(3) The marine environment in the Daya Bay has been influenced by human activities.

Acknowledgements

This study was jointly supported by the following funds awarded to Professor Danling TANG: (a) Guangdong Natural Science Foundation (05102008 and 04001306), China; (b) Key Innovation Project of Chinese Academy of Sciences (CAS) (KZCX3-SW-227-3); (c) “One Hundred Talents Program” of CAS (Ybrjh0403). Authors are grateful to projects of South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences (2007TS10 and 2007ZD03), High-tech Research and Development Program of China (2006AA100303), Chinese Ecosystem Research Network (http://www.cerndata.ac.cn), Dr. Guifeng WEI of Jinan University and the Key Innovation Project of CAS (KZCX3-SW-214).

References

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

[2] Tang D L, Kester D R, Ni I –H et al. In situ and satellite observations of a harmful algal bloom and water condition at the Pearl River Estuary in late autumn 1998 [J]. Harmful Algae 2003, 2(2): 89-99.

[3] Tang D L, Kawamura H, Dien T V et al. Offshore phytoplankton biomass increase and its oceanographic causes in the South China Sea. Marine Ecology Progress Series, 2004, 268: 31-41.

[4] Tang D L, Kawamura H, Nhu-Doan H et al. Remote sensing oceanography of a harmful algal bloom off the coast of southeastern Vietnam. Journal of Geophysical Research, 2004, 109, C03014, dio:10.1029/2003JC002045.

[5] Huang X N, Zhu Z H, Xu M C et al. Variation of water temperature in the southwestern Daya Bay before and after the operation of Daya Bay nuclear power plant. In: Pan J P, Wang Z D, Annual Research Reports (II): Marine Biology Research Station at Daya Bay. Science Publishing House, Beijing, China, 1998, 102-112.

[6] Wang W Q, Lu M L, Huang S G. Analysis on relationship among total generation rate of oxygen, biological factors and environment in Daya Bay [J]. Acta Oceanologica Sinica, 1996, 18(2): 57-65.

[7] Wang Y S, Wang Z D, Huang L M. Environment changes and trends in Daya Bay in recent 20 years [J]. Journal of Tropical Oceanography, 2004, 5(23): 85-95.

[8] Xu G Z. 1989. Environments and resources of Daya Bay [M]. Anhui Science Publishing House, Hefei, China.

[9] Tang D L, Kester D R, Wang Z D et al. AVHRR Satellite remote sensing and shipboard measurements of the thermal plume from the Daya Bay, Nuclear Power Station, China. Remote Sensing of Environment, 2003, 84(4): 506-515.

[10] Huang H H, Wang Z D, Zhang Z B et al. Preliminary study on the regional division of the distributions of Chlorophyll-a and nutrients at Daya Bay in autumn [J]. Marine Science Bulletin, 1999, 18: 32-38.

[11] Lin Y S. Researches on phytoplankton near the Daya Bay Nuclear Power Station. In: Jin Q Z, Researches on Daya Bay ecosystem (I), MBRSD (Marine Biology Research Station at Daya Bay), Chinese Academy of Sciences [M]. China Meteorological Press, Beijing, China, 1999, 59-69.

[12] Chen J F, Qi Y Z, Xiao Y Z et al. A new red tide species found *Peridinium quinquecorne Abe* in South China Sea [J]. Marine Environmental Science, 2000, 19: 20-23.

[13] Chen J F, Xu N, Wang Z H et al. Dynamics of *Pseudo-nitzschia spp.* and environmental factors in Daya Bay, the South China Sea [J]. Acta Scientiae Circumstantiae, 2002, 22: 743-748.

[14] O'Reilly J E, Maritorena S, Siegel D A, et al. Ocean color chlorophyll a algorithms for SeaWiFS, OC2, and OC4: Version 4. In: Hooker, S.B., Firestone, E.R., SeaWiFS post launch calibration and validation analyses (Part 3). NASA Goddard Space Flight Center, Greenbelt, Maryland, America, 2000, 9-23.

[15] Baith K, Lindsay R, Fu G et al. SeaDAS: data analysis system developed for ocean color satellite sensors. Eos, 2001, 82: 202.

[16] Fox M F, Kester D R, Andrews J E et al. Seasonal warming of Narragansett Bay and Rhode Island Sound in 1997: Advanced very high resolution radiometer sea surface temperature and in situ measurements [J]. Journal of Geophysical Research-Oceans, 2000, 105: 22071–22082.

[17] Mustard J F, Carney M A, Sen A. The use of satellite data to quantify thermal effluent impacts [J]. Estuarine, Coastal and Shelf Science, 1999, 49: 509-524.

[18] Poornima E H, Rajadurai M, Rao T S et al. Impact of thermal discharge from a tropical coastal power plant on phytoplankton [J]. Journal of Thermal Biology, 2005, 30: 307-316.

[19] Mallin M A, Stone K L, Pamperl M A. Phytoplankton community assessments of seven southeast U.S. cooling reservoirs [J]. Water Research, 1994, 28(3): 665-673.

南中国海北部大亚湾水温和赤潮的变化

余景[1, 2, 3]，唐丹玲[1, 2]，王素芬[1, 2]，练建生[1]，王友绍[4]

(1. 中国科学院南海海洋研究所热带海洋环境动力学重点实验室，遥感与海洋生态环境学科组，广东 广州 510301，Lingzistdl@126.com； 2. 中国科学院研究生院，北京 100039； 3. 中国水产科学研究院南海水产研究所，广东 广州 510300； 4. 中国科学院南海海洋研究所热带海洋环境动力学重点实验室，广东 广州 510301)

摘 要：近年来，大亚湾周边的经济和人口快速发展；自 1994 年大亚湾核电站运转以来，大亚湾的海洋环境和生态状况尤其受到关注。本研究利用实测和卫星遥感数据比较和分析了大亚湾水温和藻华在 1983—1993 和 1994—2004 两个时期的变化情况。结果表明：大亚湾核电站运转后（1994—2004）比运转前（1983—1993），年平均表层水温和表层叶绿素*a*含量分别升高 1.1 °C 和 1.9 mg/m^3；月平均有害赤潮（HAB）的发生次数也有增加；有害赤潮在 1994 年以前只出现在春季和秋季，而在 1994 年以后则全年都有发生；表层水温、叶绿素和有害赤潮发生次数都在 5 月份增加最明显。这些水环境和生态变化与来自大亚湾核电站的热排放以及由于人类活动增加导致的水体富营养化有关。

关键词：水温；有害赤潮；叶绿素 *a*；核电站；大亚湾