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Physical– biological coupling in the Pearl River Estuary

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ABSTRACT

The Pearl River Estuary is a subtropical estuary and the second largest in China based on discharge volume from the Pearl River. Processes in the estuary vary spatially and temporally (wet vs dry season). In the dry season at the head of the estuary, hypoxic and nearly anoxic conditions occur and NH_4 reaches $>600\,\mu M$, NO_3 is $\sim 300\,\mu M$ and nitrite is $\sim 60\,\mu M$ indicating that nitrification and denitrification may be important dry season processes in the region extending 40 km upstream of the Humen outlet. There are very few biological studies conducted in this upper section of the estuary in either the dry or wet seasons and hence there is a need for further research in this region of the river. In the wet season, the salinity wedge extends to the Hongqimen outlet and oxygen is low (35–80% saturation). Nitrate is $\sim 100\,\mu M$, silicate $\sim 140\,\mu M$; and phosphate is relatively low at $\sim 0.5\,\mu M$, yielding an N:P ratio up to $\sim$200:1 in summer. Nutrients decrease in the lower estuary and primary productivity may become potentially P-limited. Eutrophication is not as severe as one would expect from the nutrient inputs from the Pearl River and from Hong Kong's sewage discharge. This estuary shows a remarkable capacity to cope with excessive nutrients. Physical processes such as river discharge, tidal flushing, turbulent dispersion, wind-induced mixing, and estuarine circulation play an important role in controlling the production and accumulation of algal blooms and the potential occurrence of hypoxia. Superimposed on the physical processes of the estuary are the chemical and biological processes involved in the production of the bloom. For example, the 100N:1P ratio indicates that P potentially limits the amount of algal biomass (and potential biological oxygen demand) in summer. While extended periods of hypoxia are rare in Hong Kong waters, episodic events have been reported to occur during late summer due to factors such as low wind, high rainfall and river discharge which result in strong density stratification that significantly dampens vertical mixing processes. Nutrient loads are likely to change over the next several decades and monitoring programs are essential to detect the response of the ecosystem due to the future changes in nutrient loading and the ratio of nutrients.

1. Introduction

Rapid urbanization and industrialization has taken place during the past half century in the lower reaches of the Pearl River, called the Pearl River Delta, and in Hong Kong, with a particularly high intensity during the past 15 years. The total population in the Delta, Hong Kong, and Macau is now about 35 million people, and increasing. Over 100 million people live in the entire watershed of the Pearl River. As the Delta becomes crowded, further development will move to upstream areas.

The impacts from eutrophication were first observed in small water bodies (e.g. lakes) in the 1960s and 1970s (Schindler, 1977). In the past two decades, many marine coastal areas also exhibit the key eutrophication symptoms of an increase in N and P, excessive algal blooms (e.g. red tides/harmful algal blooms (HABs)), and low oxygen in bottom waters (Cloern, 2001). Therefore, nutrient pollution has become a major worldwide problem for many coastal areas (NRC, 2000). The increase in the excessive nutrients correlates with the increased use of fertilizer since the 1950s (NRC, 2000). The nutrients that are not taken up by the agricultural crops enter the ground water that drains into the river. Nutrients from rainfall, sewage, and animal manure also contribute to the nutrient loads in rivers. A summary of the quantity of wastewater discharge from Guangdong province between 1990 and 2003 is given in Table 1. The total volume of wastewater discharge has doubled, but the total volume of chemical oxygen demand has decreased by 65% due to the three times increase in the capacity of domestic sewage treatment (Table 1).

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Table 1
Basic hydrographic data of major tributaries of the Pearl River and Lingdingyang (Pearl River) Estuary (from Cai et al., 2004)

	Pearl River	Major tributaries[a]				
		West River	North River	East River	Others	Summary
Basin area ($10^3\,km^2$)		351.5	44.7	25.3	–	421.5
Discharge ($10^9\,m^3\,yr^{-1}$)						
	Wet	335	52.6	33.8	–	
	Dry	83.1	16.2	13.8	–	
	Mean	215	48.9	23	25	312
	Lingdingyang	Outlets				
		Humen	Jiaomen	Hongqimen	Hengmen	Total
Discharge ($10^9\,m^3\,yr^{-1}$)	Wet	76.3	72.6	28.1	47.8	224.8
	Dry	24.8	21.5	6.2	13.5	66.1
	Mean	56.9	52.6	18.6	62.5	160.6
	% of total	35.5	32.7	11.6	20.2	

Note that data from other Chinese documents are about 10% higher in all values.
[a] Data from Kot and Hu (1995).

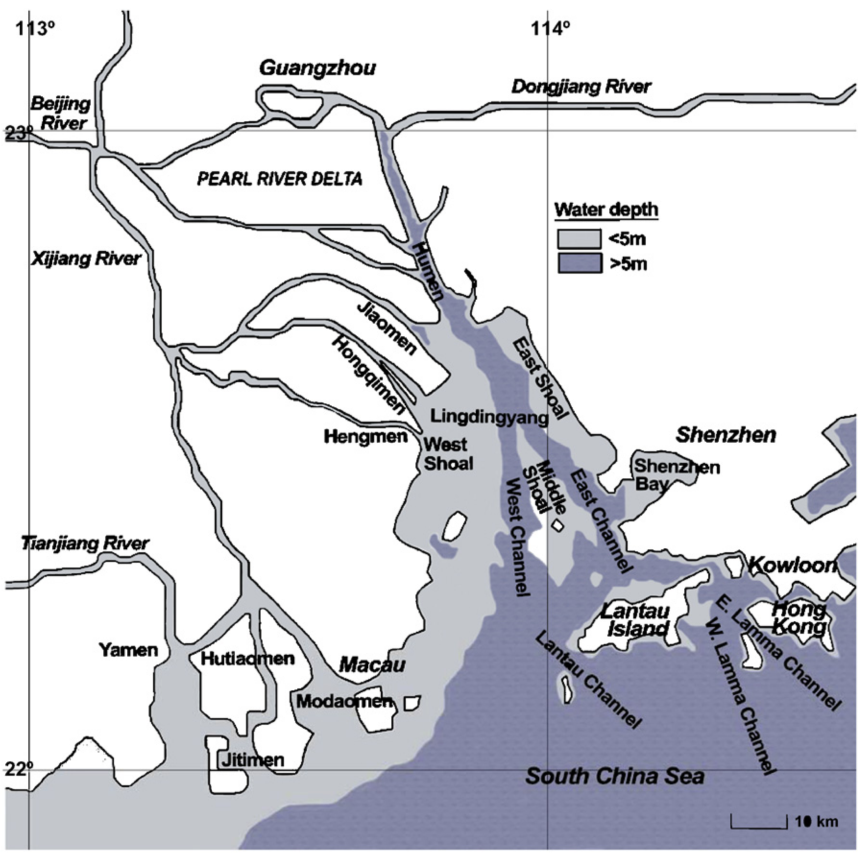

Fig. 1. Map of the Pearl River Estuary showing the three main rivers (East, North, and West Rivers), the four main outlets entering into the upper estuary (Humen, Jiaomen, Hongqimen, and Hengmen) and the four outlets that discharge directly into the South China Sea (Modaomen, Jitimen, Hutiaomen, and Yamen).

The Pearl River Estuary (PRE) is located midway along the northern boundary of the South China Sea. The coast has a NE–SW orientation and the adjacent shelf is 150–250 km wide (Fig. 1). It is a subtropical estuary with annual rainfall from 1600 to 2300 mm.

The Pearl River or Zhujiang River is China's third longest river (2200 km), after the Yangtze and Yellow Rivers. It is located on the northern shelf of the South China Sea, just west of Hong Kong and considered to be a subtropical river since it lies south of 23°N. The Pearl River delivers $350\times10^9\,m^3\,yr^{-1}$ of fresh water with a sediment load of 85×10^6 tons yr^{-1} into the South China Sea via three estuaries, Lingdingyang, Modaomen, and Huangmaohai (Fig. 1). This paper will focus mainly on the Lingdingyang (the region of the PRE that is upstream of Shenzhen Bay or Deep Bay) that receives about 50% of the Pearl River freshwater discharge. We also include some discussion of the section below Shenzhen Bay and some of the western and southern waters of Hong Kong since the estuarine plume reaches these areas in the summer when river discharge is high.

Beyond the estuary, the seasonal monsoon winds and coastal currents govern the coastal transport. The northeast monsoon winds in winter produce a cyclonic circulation in the South China Sea and a northeastward flowing Guangdong coastal current. In summer, the southwest monsoon winds produce an anti-cyclonic circulation in the South China Sea and the South China Sea warm current flows northwards (Su, 2004).

The annual average flow rate of approximately 10,000 $m^3 s^{-1}$ for the Pearl River is exceeded only by the Yangtze River. The Pearl River is 2200 km long and drains an area of 453,700 km^2. Most of the drainage basin is in Southern China, but a small part is in northern Vietnam. Parts of the provinces of Yunnan, Guizhou, Guangxi, Guangdong, Hunan, and Jiangxi drain to the Pearl River system. In the western part of the drainage basin, carbonates are abundant and major ions and total alkalinity (TAlk) are high in the rivers. In contrast, the eastern section of the drainage basin is mostly granite and the rivers have low total ions and low TAlk (Cai et al., 2004). The width of the estuary varies from 15 km at the northern end to 35 km at the southern end. Most of the PRE is quite shallow and the average depth is about 4.8 m (range from 2 to 10 m). There are two longitudinal deep channels (Fig. 1). The west channel runs down the PRE and connects to Lantau Channel and the other east channel passes around the northeast tip of Lantau Island and connects to the shelf via East Lamma Channel. The area of the PRE is about 1900 km^2.

Since eutrophication is a major issue in the PRE, this paper will focus on the estuarine ecosystem response to this increase in nutrient loading over the past several decades. This review provides an insight into the complex temporal and spatial dynamics of physical, chemical, and biological factors that influence nutrient and phytoplankton dynamics in the PRE.

2. Physical processes

The Pearl River has three major branches (Xijiang, West River; Beijiang, North River; and Dongjiang, East River) in the upper drainage basin and a network of small rivers in the river delta area (Fig. 1). The Xijiang River is the largest and contributes 77% of the water discharge (Table 2) and 86% of the suspended sediment (Zhou et al., 2006). Freshwater discharge occurs through eight outlets (called "gates" in Chinese) located on the western side (Fig. 1). The four northern most distributaries (Humen, Jiaomen, Hongqimen, and Hengmen) discharge about half of the Pearl River discharge directly into the PRE (Table 2). The four southwestern outlets (Modaomen, Jitimen, Hutiaomen, and Yamen) discharge directly into the South China Sea (Fig. 1). The largest discharge passes through Modaomen (west of Macau). Humen (at the head of the estuary) is the second largest river inlet. Hong Kong is situated to the east of the PRE. The PRE receives 53% of the river runoff from the Pearl River drainage basin, i.e. about 5300 $m^3 s^{-1}$ in terms of flow rate. High discharge occurs for at least 3 months in the summer, and 80% of the total flow occurs between April and September, with the ratio between maximum and minimum discharge varying between three and six times. The Pearl River discharge is about 4000 $m^3 s^{-1}$ in winter and peaks at 20,100 $m^3 s^{-1}$ in summer and hence a large freshwater plume forms in summer at the mouth of the estuary.

The suspended sediment load of the Pearl River is less than other rivers in China (Wai et al., 2003). The annual sediment transport is about 90×10^6 tons with nearly 80% coming from the West River. About 95% of the sediment load arrives during the wet season. The sediment is mainly composed of clay and silt. The suspended sediment concentration (SSC) is generally <0.04 kg m^{-3} (40 mg l^{-1}). SSC is higher during the wet season (0.04–0.30 kg m^{-3}) and lower during the dry season (0.02–0.19 kg m^3). In turbidity maximum zones, SSC can be >0.1 kg m^{-3} (Xu, 1985; Zhao, 1990) and these zones are located near or upstream of the salt-wedge intrusion (Wai et al., 2003). Deposition rates are >2 cm yr^{-1} and higher in some local areas (Zhou et al., 2006).

The PRE is a complex estuary with marked variations in bottom topography, and seasonally dynamic variations in freshwater discharge, monsoon winds, and estuarine circulation. The coastal circulation governs the transport and distribution of physical and water quality parameters such as temperature and salinity. The complexities of the circulation have been described by Wong et al. (2003, 2004a, b) and Dong et al. (2004) and are not included here.

The water column of the Pearl River plume exhibits a large wet and dry season variation due to the five times higher summer discharge compared to the dry season. During the dry season, the temperature and salinity are vertically homogeneous, except for some areas with very low salinity in the western part of the estuary (Wong et al., 2003). The temperature ranges from 16 to 20 °C with warmer water on the eastern side of the estuary (Huang and Ye, 1995; Dong et al., 2004). The northeast monsoon winds drive a southeastward coastal current and the salinity in the estuary seldom reaches 32, even though river discharge is greatly reduced. The salinity at Humen is about 10 at the surface and 20 at depth (Zhang, 1984; Xu, 1985). During the dry season, the salinity front of both the surface and deep water is oriented along the axis of the estuary and is closer to the western shoreline (Fig. 2A, B). The salinity front is inside the entrance of the estuary near Deep Bay, unlike most other estuaries (Dong et al., 2004). The river plume flows seaward along the west side of the estuary due in part to the strongly developed N–S salinity front. The surface front broadens when the NE winds are weak, but the bottom front is not affected by winds.

Table 2
Quantity of wastewater discharge from Guangdong Province, China between 1990 and 2003

	1990[a]	1995[a]	1996[a]	1997[a]	1998[b]	1999[b]	2000[b]	2001[b]	2002[b]	2003[b]
Total volume of wastewater discharged ($\times 10^6$ tons)	2515	3816.5	3714	4198	4341	4287	4475	5114	4904	5464
Domestic sewage (% of total discharge)	44	56	57	70	73	73	75	78	70	73
Industrial effluent (% of total discharge)	56	44	43	30	27	27	25	22	30	27
Total volume of chemical oxygen demand emission in wastewater ($\times 10^6$ tons)	0.695	1.12	1.06	0.95	0.36	0.34	0.28	0.216	0.207	0.211
Overall rate of domestic sewage treatment (%)	–	–	–	9.0	–	–	–	–	–	35
Overall rate of industrial wastewater treatment (%)	56.8	77.1	80.2	85.3	89.2	–	96.2	96.2	–	–
Overall rate of industrial wastewater recovered (%)	–	43.4	49.8	45.0		89.9	–	–	–	–
Rate of industrial wastewater meeting discharge standard (%)	47.1	56.3	57.7	56.7	61.6	64.9	81.8	81.8	78.3	82.9
Capacity of domestic sewage treatment ($\times 10^6$ tons)	–	–	–	–	511	–	–	–	–	1455

Also included are the percentage of domestic sewage and waste treatment rate in the total discharged waste (from Dai et al., 2006).
[a] From Ho and Hui (2001).
[b] Based on Environmental Status Bulletins of Guangdong Province, China at ⟨http://www.gdepb.gov.cn/⟩.

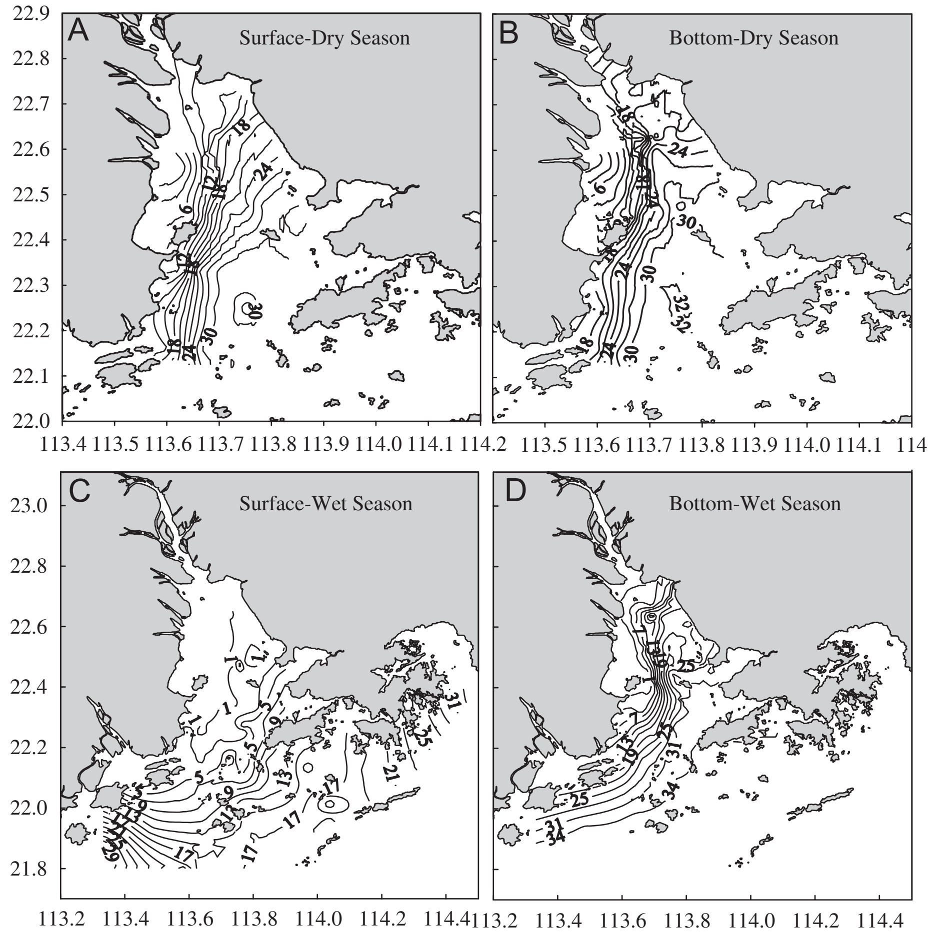

Fig. 2. Salinity contours in the Pearl River Estuary: (A) surface waters in the dry season, (B) bottom waters in the dry season, (C) surface waters in the wet season, and (D) bottom waters in the wet season (from Wong et al., 2003).

During the summer wet season, summer upwelling near the mouth of the estuary and the northeastward coastal current influence the water column stability (Li, 1993). The temperature and salinity of the bottom water near the mouth range from 27 °C and >33 respectively to >30 °C and <1 at the head of the estuary (Dong et al., 2006). The estuary is highly stratified with a very low salinity surface layer and a strong halocline at 4–7 m. The estuary is funnel shaped and widens down estuary and the low salinity upper layer becomes thinner (1–3 m) seawards. The thickness of the low salinity upper layer increases westward in the PRE and there is a cross-estuary inclination in the pycnocline (Dong et al., 2006). The bottom salinity increases across the estuary from west to east (Fig. 2D). Oceanic water with a salinity of about 33 moves into the PRE through Lantau Channel and also through East Lamma Channel and enters the estuary at the middle reach (Fig. 1). There is a deep water salinity front that runs along the axis of the estuary with isohalines parallel to the deep channel and it turns west, parallel to the coastline outside the estuary (Fig. 2D). In contrast, the surface water salinity front extends across the estuary (Fig. 2C).

The seasonal variation in the monsoon wind speed and direction plays an important role in governing the spreading of the Pearl River plume outside the estuary (Dong et al., 2004). During the wet season with southerly winds (wind speeds generally <6 m s^{-1}), the horizontal extension of the plume is large since the high river discharge is advected eastward and offshore by the coastal current induced by the upwelling, favorable winds (Dong et al., 2004, 2006). During the dry season with northeasterly winds (wind speeds of 7–10 m s^{-1}), the plume is advected westward by the northeasterly induced coastal current and since the river discharge is much smaller, the horizontal extent of the plume is also small.

The tides in the PRE are generated by the interaction of the Pacific Ocean tides with the complicated topography as they propagate through the Luzon Strait (Ye and Preiffer, 1990). Tides are mixed and predominantly semi-diurnal. In the coastal waters of Hong Kong at the mouth of the estuary, the mean tidal range is 1.7 m with a range from 1 m during neap tides to up to 2 m during spring tides, and there is little seasonal variation (Lee et al., 2006). The tide can vary from semi-diurnal during a spring tide to nearly diurnal during a neap tide (Lee et al., 2006). As the tidal wave progresses upstream from the coastal water into the estuary, the tidal energy is concentrated and the tidal range is amplified because of the inverted funnel-shaped topography. For example, the M2 tidal range increases from 0.8 m in Hong Kong to 1.18 m in Guangzhou at the upstream end of the estuary. In the cross-estuary section, the east has larger tidal ranges (Mao et al., 2004).

Tidal circulation in the PRE results from the interaction of the coastal tides with the river discharge, local topography, and bathymetry. In the dry season, the PRE resembles a vertically mixed estuary with significant horizontal salinity gradients. In the wet season, the large river outflow gives rise to a salt-wedge type of circulation, with a saltwater intrusion via the eastern channel, while the river outflow dominated the western channel. The mean tidal currents are seaward in the upper layer and along-estuary and cross-estuary components are about 0.5 and 0.1 m s^{-1}, respectively. Ebb and flood tides are affected by the wind speed and direction. The peak flood and ebb surface velocities during a neap tide are about 70–80% of spring tide values and ebb velocities are greater than flood velocities (Lee et al., 2006). The ebb duration typically exceeds the flood duration by about 2.8 h in the dry season and 1.0 h in the wet season (Dong et al., 2006). The flood tide duration decreases from 6.5 h at the mouth of the estuary to about 5.5 h at the head of the estuary (Xu, 1985; Zhao, 1990). The pattern of residual currents in the PRE is counter-clockwise with stronger flood currents on the east side and stronger ebb currents on the west side.

During the dry season, the coastal current flows from NE to SW and the Pearl River flow turns to the west (Macau side) due to the NE monsoon winds and the Coriolis effect. During the wet season with SW monsoon winds, some of the Pearl River discharge moves into Hong Kong waters. The residual currents in the surface layer are stronger than the bottom layer due to the rainfall and the high river discharge.

3. Physical–biological coupling in relation to nutrient and phytoplankton dynamics

3.1. Dry season

During the dry season, the eutrophication impacts on the upper estuary are serious due to the low river discharge. Large areas of the upper estuary are hypoxic, nutrient concentrations (especially NH_4) are very high and very high CO_2 concentrations indicate that the upper estuary is strongly heterotrophic.

Only a few studies have been conducted at the head of the estuary near Humen and upstream. This section is 50 km long, 2.2 km wide, and the average water depth is about 6 m. It receives a high pollutant discharge and organic load from industrial cities such as Foshan and Dongguan. Hence the average dissolved oxygen (DO) concentration has declined from 113 to 75 μmol O_2 kg^{-1} from 1990 to 1998 (Zhang et al., 1999).

Dai et al. (2006) examined the upper reach of the PRE from the Humen outlet upstream to Guangzhou during a very dry month in February 2004. Due to the low river flow, the water residence time was prolonged. The seawater intrusion was much further upstream than usual. The water column was slightly stratified at Humen due to the salt-wedge penetration and the salinity was 17 compared to near 0 in summer. Some seawater penetrated 50 km upstream to Guangzhou where the salinity was still ~1.

DO concentrations in surface waters in the upper reach of the estuary for various seasons are given in Table 3. In the vicinity of the Humen outlet, Dai et al. (2006) observed that surface DO was 150 to <30 μmol O_2 kg^{-1} near Guangzhou during February 2004 (Fig. 3a). The water column was well mixed and hence most of the water column was oxygen depleted. The pCO_2 concentrations were inversely related to DO and increased from <2000 μatm at Humen to >7000 μatm, about 40 km upstream where DO was very low indicating that the upper estuary was strongly heterotrophic (Fig. 3). Dissolved organic carbon (DOC) varies widely in the upper part of the estuary (100–170 μM) and is ~100 μM in the lower estuary (Zhang et al., 1999).

The concentrations of NH_4, NO_3, and NO_2 in surface waters are very high and higher than other Chinese rivers (Cai et al., 2004; Dai et al., 2006). About 40 km beyond Humen, NH_4 reaches a maximum of >600 μM, while NO_3 was ~300 μM and NO_2 was ~60 μM (Fig. 3d). More extensive monitoring during January to May 2004 revealed an alarmingly high average NH_4 concentration of ~540 μM (http://www.gemc.gov.cn). The high NO_3 and NO_2 can be explained by nitrification, the oxidation of ammonium, and nitrite to nitrate. Nitrification rates of about 5 mmol N m^{-3} d^{-1} have been reported (Dai et al., 2006). Thus, nitrification is partially responsible for the observed decrease in oxygen and TAlk and the production of CO_2 at low salinities (Fig. 3c). Luo (2002) experimentally proved the importance of nitrification by adding a nitrifying inhibitor to samples from the Guangzhou region. Very high nitrification rates have been reported in sediment samples from this same region and high concentrations of nitrous oxide suggest that denitrification also occurs (Xu et al., 2005). Nitrification generates a source of nitrate for denitrifying bacteria and denitrification leads to a loss of nitrogen as N_2 gas and/or nitrous oxide to the atmosphere. Sulfate reduction probably also occurs in these low-oxygen waters, but there is no information on its importance. Therefore, in this upstream part of the estuary, sewage discharge and other organic inputs enhance oxygen depletion, nitrification and denitrification (N loss to the atmosphere), and carbon dioxide production (Fig. 3c). Intense nitrification has also been observed at intermediate salinities in the Mississippi River plume (Pakulski et al., 1995, 2000).

While there are some initial studies on the chemistry in the upper part of the river, to our knowledge, there is no information on primary productivity and phytoplankton biomass and species composition in this upstream area. This should be addressed in future studies.

In the area downstream of Humen, there have only been a very few studies. Guo et al. (this volume) conducted a seasonal study of dissolved inorganic carbon (DIC) and TAlk and found that they are both higher in the dry season than the wet season and they decrease down the estuary. There is little difference in the silicate–chlorinity relationship between winter and summer samples (Zhang et al., 1999). Ammonium and phosphate concentrations are higher in winter than summer. To our knowledge there are no reported data on primary productivity for the lower estuary in winter.

3.2. Wet season

3.2.1. Nutrients

During the wet season, the high river discharge dilutes the nutrient and organic loads. Productivity and Chl biomass are low due to turbulent river flow and turbidity that decreases light availability for phytoplankton growth. At the outer part of the riverine plume, turbidity decreases and a phytoplankton bloom may occur, especially during periods of strong stratification and low winds (Fig. 5). Due to the high 100N:1P ratio in the river, the

Table 3
Dissolved oxygen in the surface water of the Pearl River Estuary (from Dai et al., 2006)

Survey time	Location	DO (μmol O_2 kg^{-1})	Salinity	Reference
July 2000	Humen vicinity	96–176	0.1–1.8	Zhai et al. (2005)
May 2001	Humen vicinity	31–190	0.1–0.6	Zhai et al. (2005)
November 2002	Humen upstream	15–62	0.16–0.3	Dai et al. (this volume)
February 2004	Humen upstream	12–68	1.0–4.0	Dai et al. (2006)

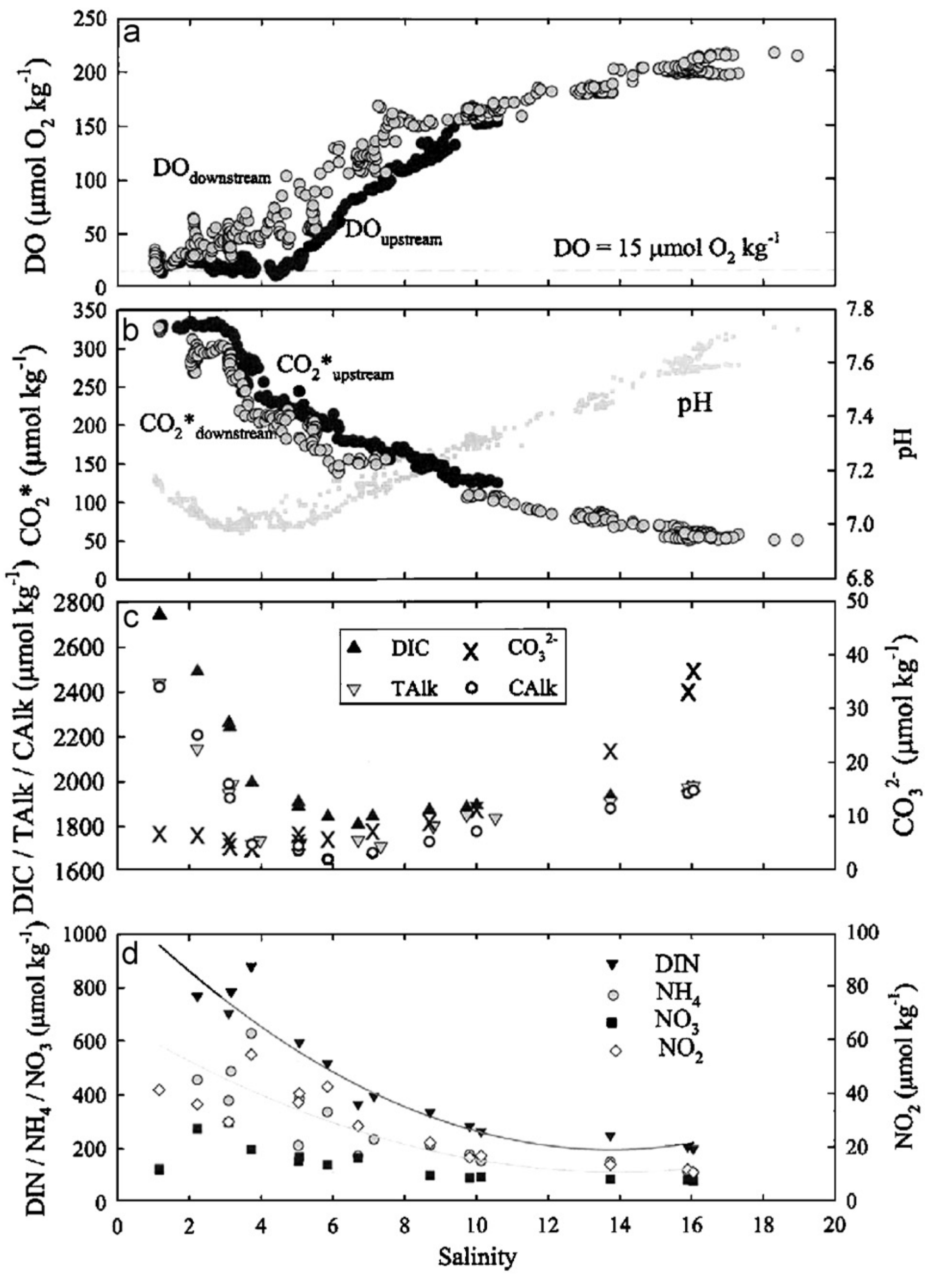

Fig. 3. Mixing processes of: (A) dissolved oxygen (DO), (B) CO_2 and pH, (C) dissolved inorganic carbon (DIC), total alkalinity (TAlk) and carbonate, and (D) nutrients including NO_3, NH_4 and dissolved inorganic nitrogen (DIN), and the distribution of these parameters in relation to salinity in the PRE (from Dai et al., 2006).

phytoplankton bloom may potentially become P-limited. This is in contrast to the Mississippi River where N limitation is more frequent (Lohrenz et al., this volume).

The area upstream of Humen has not received much study compared to the middle and lower estuary. During this summer wet period, estuarine circulation is strong and saline water enters the estuary as a salt wedge at the bottom and freshwater flows out of the estuary at the surface (Fig. 4). During July 2000, the salt wedge extended to near the Hongqimen outlet and beyond this point the river was well mixed, with water temperatures about 28–30 °C (Cai et al., 2004). Stratification is strong in summer with haloclines at ~1 m and also near the bottom layer (Zhang et al., 1999).

For about 20 km upstream of Humen, salinity was <1 and DO was very low (35–80% saturation) and pCO_2 was very high (4200 μatm; Cai et al., 2004). High NO_3 (75–100 μM) and high SiO_4 (130–140 μM) and low PO_4 (0.2–0.4 μM) were observed. Suspended solids ranged from 30 to 150 mg l^{-1} (Zhang et al., 1999) and the turbidity led to reduced light penetration (1% light depth was ~1 m), low phytoplankton biomass <16 to 20 mg chl m^{-2}) and low primary productivity (<0.1 g C m^{-2} d^{-1}) (Yin et al., 2000). Historical data for nutrients and inorganic carbon are shown for the near-zero salinity zone (Table 4). There is no apparent trend in these parameters over the past two decades, but this may be due to insufficient data.

In the middle and lower estuary, the water column is strongly stratified due to the low salinity from the high river discharge (Fig. 5). This low salinity, 30–50 m thick surface layer was observed to extend ~300 km offshore (Cai et al., 2004) with pronounced movement to the northeast due to the southwest monsoon winds.

In the estuary, NO_3, PO_4, and SiO_4 concentrations varied especially near the entrances of the four outlets. The largest input of dissolved inorganic nitrogen (DIN) and PO_4 comes from the Humen outlet (~40%), followed by Jiaomen (~30%) (Table 5). Their concentrations were typically twice as high during an ebb tide as compared to the flood (Huang et al., 2003). They behaved nearly conservatively in the area where S<20 and there was little seasonality, but beyond this area, NO_3 and SiO_4 were actively taken up (Fig. 3d). Phosphate behaves non-conservatively and remains generally <1 μM throughout most of the estuary, probably due to fast regeneration from particulate phosphorus and P adsorbed to sediments (Zhang et al., 1999). Nitrite (1–3 μM) and NH_4 (1–6 μM) were relatively high, probably due to recycling processes of organic matter. Near Shenzhen Bay (also called Deep Bay), NH_4 and PO_4 concentrations were very high (~25 and 1 μM, respectively), possibly due to sewage and other waste inputs from the city of Shenzhen (EPD, 2002; Huang et al., 2003). Thus, Shenzhen Bay injects a considerable amount of NH_4 and PO_4 into the eastern side of the middle section of the estuary. It is surprising that the PO_4 concentration in the upper part of the estuary was lower than in the mid to lower estuary. The DIN concentration is usually higher in the surface water of the lower estuary, while PO_4 was similar in the surface and bottom water, indicating that the PO_4 load from the river does not enhance the PO_4 concentration relative to PO_4 from the vertical mixing of deep water to the surface. During the past decade, the DIN and PO_4 concentrations appear to have remained fairly constant, although Huang et al. (2003) suggest that these concentrations have declined during this decade.

The high anthropogenic inputs of nitrogen from the river (DIN ~100 μM) and rainfall (~50–300 N:P) yield a 100N:1P ratio that is about seven times higher than the normal Redfield ratio of 16N:1P that is optimal for phytoplankton growth (Fig. 4). In contrast, the natural nutrient sources are nutrient-poor deep water and they are brought to the surface by summer upwelling and strong estuarine circulation driven by high river discharge (Fig. 4). This upwelled nitrogen-poor water (N:P ~10:1) dilutes the nutrient-rich surface water and helps to reduce eutrophication effects. The N:P ratio decreases from >100 in the upper estuary to 30–40 in the lower estuary, mainly due to the decrease in DIN by biological utilization, since the PO_4 concentration was relatively constant in the upper and lower estuary, perhaps due to recycling (Zhang et al., 1999; Huang et al., 2003; Yin et al., 2004b; Dai et al., 2006). The very high 100N:1P ratio in the estuary is in contrast to the Mississippi River (N:P = ~30) that has a three times higher P concentration (~3 μM) than the Pearl (~1 μM) (Rabalais et al., 1996; Lohrenz et al., this volume). The Si:N ratios (1.2–1.7) in the PRE are similar to temperate nitrogen-impacted rivers such as the Changjiang and Mississippi Rivers (Rabalais et al., 1996; Zhang et al., 1999).

3.2.2. Nutrient and light limitation and primary productivity

Due to the high N input from the Pearl River in summer, there is a large area of the lower estuary and nearby Hong Kong waters that is potentially P-limited in the summer (Zhang et al., 1999; Yin et al., 2000). P limitation has been observed in the northern region of the South China Sea (Ning et al., 2004), and in other coastal areas in China (Harrison et al., 1990). Potential limitation means that while PO_4 concentrations are seldom <0.01 μM, possibly due

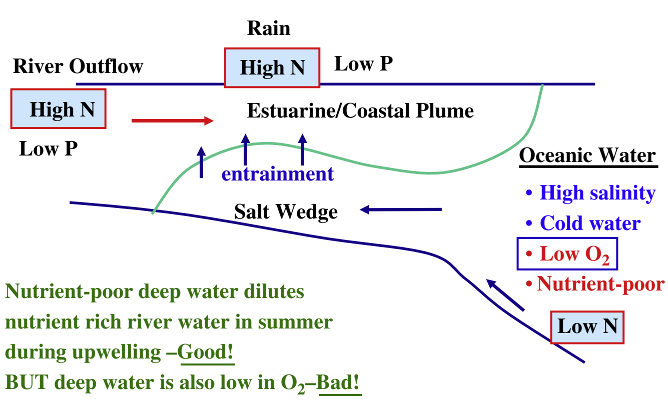

Fig. 4. Conceptual diagram showing estuarine circulation due to high Pearl River discharge in summer. Vertical section of the Pearl River Estuary showing river and rain nutrient inputs, the estuarine/coastal plume and salt-wedge formation (from Yin and Harrison, this volume).

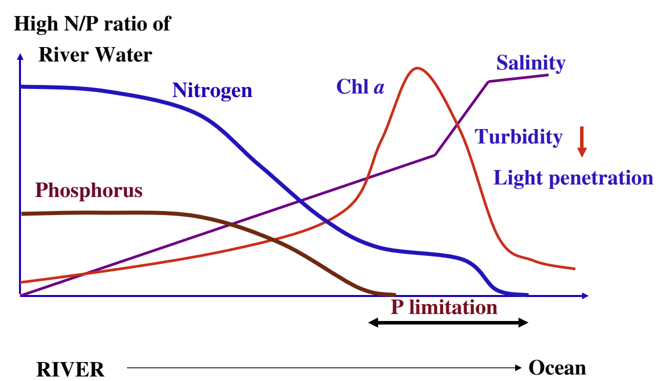

Fig. 5. Conceptual diagram showing the spatial dynamics of nutrients and phytoplankton biomass (Chl *a*) along a salinity-gradient transect down the estuary.

Table 5
Input amounts of DIN and phosphate from four river channels (tons/year) and percent of total in brackets (from Huang et al., 2003)

Items	Humen	Jiaomen	Hongqimen	Hengmen
DIN	77208 (43)	44629 (24)	18553 (10)	38903 (22)
Phosphate	1808 (36)	1525 (30)	651 (13)	1004 (20)

Table 4
Historical data of nutrient and inorganic carbon at the near-zero salinity zone of the Pearl River flowing into the Lingdingyang (Pearl River) Estuary (from Cai et al., 2004)

Time of survey	DIN (μM)	SiO_3 (μM)	PO_4 (μM)	TAlk (μM)	DIC (μM)	References
1980s (Xijiang)	47		0.11			Duan and Zhang (2001)
May 1982	77.2	120	–			Lin et al. (1985)
January 1984	90.5	138	–			Lin et al. (1985)
Summer 1996	69	160	0.48	500–2000		Zhang et al. (1999)
September 1994				670–1210		Li et al. (1999)
August 1997	90±15					Cai et al. (2002)
July 1999	>80					Yin et al. (2001)
July 2000	75–110	126–141	0.2–1.2	1050–1650	900–1500	Cai et al. (2004)

to PO_4 regeneration processes, bioassay experiments onboard the ship indicate that PO_4 is quickly depleted and surplus NO_3 is left at the end of the incubation (Yin et al., 2000, 2001; Yin and Harrison, this volume). This surplus NO_3 is most likely exported further offshore beyond the river plume (Fig. 5; Zhang et al., 1999; Yin et al., 2001, 2004b).

While nutrient ratios may indicate which nutrient may potentially become limiting for algal growth, it is the concentration of the limiting nutrient that determines the amount of algal biomass produced (the yield) and hence the amount of oxygen consumed during algal decomposition in the bottom waters. Since the N:P ratio is >16:1 in summer in the outer estuary, then the concentration of P will control the amount of algal biomass produced (i.e. additional biological oxygen demand, BOD). According to Redfield stoichiometry and assuming sufficient light, 1 μM P and 16 μM N will produce about 16 μg chl l^{-1} and when this algal biomass is decomposed, and 138 μM or 4.4 ml l^{-1} of oxygen is consumed. Hence, the concentration of PO_4 in this estuary can potentially influence the amount of algal biomass produced and subsequently the amount of O_2 consumed when organic matter is decomposed.

The suspended solids decrease rapidly to ~10 mg l^{-1} as water flows down the estuary and 1% light depth reaches 4–6 m (Huang et al., 2003; Yin et al., 2004b). This decrease in turbidity and increase in light availability for algal growth is linked to the production of algal blooms in the outer estuary (Fig. 5). Suspended solids are typically twice as high near the bottom as at the surface, probably due to resuspension of bottom sediments (Zhang et al., 1999). Similarly NH_4 can be 5–10 times higher at depth compared to the surface, suggesting remobilization of bottom NH_4 from bottom sediments (Zhang et al., 1999). Since the estuary is strongly stratified during the wet season, these bottom resuspended particles and higher nutrients may not reach the surface. Primary productivity is probably limited by light due to turbidity and some mixing, and varies from 1 to 4 g C m^{-2} d^{-1}, while chl *a* ranges from 20 to 70 mg m^{-2} (Yin et al., 2000; Yin, 2002). Chl in the Shenzhen Bay area was about three times higher than other areas in the estuary due to the very high concentration of nutrients in the bay (Huang et al., 2003). For the outer estuary and inner shelf (major plume area) primary productivity is about 0.8 g C m^{-2} d^{-1} and at the outer shelf and slope, it decreases to 0.1–0.2 g C m^{-2} d^{-1} (Cai et al., 2004). Summer bioassay experiments demonstrated that low salinity regions were P-limited, while the outer estuary was N- or Si-limited (Yin et al., 2000, 2001, 2004b; Zhang et al., 1999). In addition, rainfall further enhances potential P limitation since the N:P ratio of rain is 50–300:1 and the N:Si ratio is 3–6:1 which would contribute to Si limitation (Yin et al., 2000; Zhang et al., 1999). Data on nutrient inputs from the sediments are lacking and this data gap should be addressed in future studies.

Iron has been suggested to be the factor that limits primary productivity by Zhang (2000). However, additional trace metal bioassay experiments conducted in June 2004 indicated that P was the first nutrient to become limiting and iron limitation played a very secondary role (Miao et al., 2006). A comparison of nutrient concentrations, nutrient ratios and annual primary productivity with other large rivers in China and other areas is summarized in Table 6.

DOC and colored dissolved organic matter (CDOM) were measured during July 1999 along a transect down the estuary (Chen et al., 2004). The highest CDOM (~1.40 m^{-1}) occurred in the upper estuary, indicating that the river was the main source, but the CDOM concentrations were relatively low (<1.0 m^{-1}) compared to other estuaries of the world. Thus, CDOM is not a major factor in reducing light availability for phytoplankton growth in the upper estuary. CDOM showed non-conservative mixing properties. In contrast, DOM showed little variation with the salinity gradient and concentration ranging from 70 to 100 μM, except in an area with about 20 μg chl l^{-1} (Chen et al., 2004).

Very few studies have been conducted on bacterial abundance and there is no studies to date on bacterial productivity. The microbial loop most likely plays a very important role in the estuary and certainly warrants further study. Wu et al. (2004) used the terminal restriction fragment length polymorphism pattern of amplified 16S rRNA sequences to assess the free-living bacterial community in the surface waters of the PRE. The TRF pattern revealed nine dominant bacterial groups with the dominant species belonging to the γ-subdivision of proteobacteria and the *Bacillus/Clostridium* group of Firmicutes (Wu et al., 2004).

4. Eutrophication impacts

The DO concentration in the bottom waters of estuaries is one of the major impacts of eutrophication and it may lead to a large area of hypoxia (DO <2 mg l^{-1}), such as the "dead zone" at the mouth of the Mississippi River (Rabalais et al., 2002). The PRE and Hong Kong waters do not have extensive areas of long-lasting

Table 6
Discharge, concentrations of dissolved inorganic nutrients and carbon, elemental ratios, and average annual primary production of major river system (from Cai et al., 2004)

Climate zone	River	Discharge ($\times 10^3$ m^3 s^{-1})	DIN	DIP	SiO_3	DIC	TAlk	C:N	N:P	Si:N	Annual (PP g C m^{-2} y^{-1})
			(μM)			(μM)		(mol: mol)			
Tropical	Amazon	188	12	0.6	132	0.6[a]	0.6[a]		20	11	430–580[a]
	Zaire	49	7.2	0.8	165				9	23	83
	Orinoco	42	6.6	0.2	86				33	13	137
Subtropical	Zhujiang (Pearl River)	10	50–110[b]	0.2–1.2[b]	120–170[b]	1.5[c]	1.65[c]	20	100–600[c]	1.2–1.7[c]	~220[d]
Temperate	Changjiang	27	40	0.62	125		1.97[e]		65	3	274
	Mississippi	16[b]	101	3.1	108	2.1–2.9[f]	2.1–2.9[f]		33	1	584
	Huanghe	1.5	134	0.99	–		2.98[e]		135	–	135

[a] Ternon et al. (2000).
[b] From Table 4.
[c] Cai et al. (2004).
[d] Based on July 2000 data of 0.8 g C m^{-2} d^{-1} (within the estuary) and the assumption of an effective annual growth period of 9 months.
[e] Zhang (1999) and references therein.
[f] Cai (2003).

hypoxia, although small-scale, short-lived low DO concentrations near $2\,mg\,l^{-1}$ have been observed, especially in the summer when the waters became highly stratified due to rainfall and river discharge (Yin et al., 2004a). The oxygen concentration in bottom waters in Hong Kong waters has been relatively constant over the past 25 years (Yin et al., 2004a). Looking at the historical record, during the summer of 1981 and 1984, DO was $<4\,mg\,l^{-1}$, but rarely $<3\,mg\,l^{-1}$ (Yin et al., 2004a). A 9-year record from 1990 to 1998 showed that DO decreased in summer, but was rarely $<3\,mg\,l^{-1}$ and there was no apparent decreasing trend (Yin et al., 2004a). The reasons why hypoxia is not more prevalent in the PRE and Hong Kong waters are probably due to good flushing via strong currents and estuarine circulation in the summer (Lee et al., 2006). Also, shallow water depths (5–20 m) make wind mixing an effective method of delivering oxygen to the bottom waters. In addition to these physical controls on hypoxia, Yin et al. (2004a, b) have suggested that the low PO_4 concentrations relative to nitrogen (N:P ~100:1) may limit the phytoplankton biomass production through P limitation and hence the amount of organic matter sinking to depth.

5. Plankton community

Phytoplankton species diversity is high with about 200 species of diatoms and 70 species of dinoflagellates (Lin et al., 1985; Huang et al., 2004). In the upper part of the PRE near Humen, the estuarine diatom *Melosira granulata* is often dominant (Huang et al., 2004), while *Skeletonema costatum* and *Chaetoceros* spp. are the dominants in the lower estuary. The annual average abundance ranges from 5×10^6 to 6×10^9 cells m^{-3} and there appears to be an increase in the abundance in recent years (Yan et al., 2006). During the wet season, *Melosira* is dominant in the enlarged brackish water area of the estuary, while *Skeletonema* is more widely dominant in the dry season when the salinity is higher (Huang and Ye, 1995). Over the past 20 years, it has been suggested that the diatom species composition has changed with the recent appearance of *Nitzschia delicatissima* and *Staurastrum polymorphum* (Yan et al., 2006). There is an urgent need to determine the importance of picoplankton in the estuary.

Most HABs occur in the eastern waters of Hong Kong (Yin, 2003), but outbreaks of HABs also occur on the eastern side of the mid-section of the PRE and especially in Shenzhen Bay (Yan et al., 2006) and in the southern waters of Hong Kong. The most common HAB species are the dinoflagellates *Noctiluca scintillans*, followed by *Gymnodinium* sp. Diatoms such as *S. costatum*, *Thalassiosira* sp., and *Chaetoceros* sp. are also important c omponents of HABs since their high biomass may sink and contribute to low oxygen in bottom waters (Yin, 2003; Yan et al., 2006).

The response of the copepod community structure to eutrophication has not been well documented in this estuarine system. During the summer of 1999 and the winter of 2000, mesozooplankton were dominated by copepods. In the summer, *Acartia spinicauda*, *Pavocalanus crassirostris*, *Oithonarigida*, *Paracalanus aculeatus*, and *Euterpina acutifrons* were numerically dominant, while during winter *Paracalanus serrulus*, *P. crassirostris*, *Paracalanus parvus*, *A. spinicauda*, and *Oithona* spp. were dominant (Tan et al., 2004). Li et al. (2006) observed that coastal species such as *Euchaeta concinna*, *Acetes japonicus*, and mysids entered the upper part of the estuary in winter. The grazing impact of the zooplankton, especially the copepods, varied seasonally from 1 to 75% of the chlorophyll standing stock in summer and winter, respectively (Tan et al., 2004). However, the influence of zooplankton grazing on the food web structure remains largely unknown in this region. There is no information on the importance of microzooplankton and therefore further studies are definitely needed to determine their importance in the estuary.

6. Episodic events/bloom dynamics

While the monthly or bimonthly data sets from the long-term water quality monitoring program in Hong Kong waters have provided excellent information on seasonal and annual trends and effects of eutrophication, we have a limited understanding of the importance of short-lived episodic events such as nutrient input and wind mixing due to storms and typhoons, river discharges due to heavy rain, and short-term meteorological event triggered by El Niño (e.g. extended period of warm temperatures).

For example, primary productivity has been observed to be very dynamic in summer and wind events play an important role in regulating productivity (Yin et al., 2004c). During July 18–19, 1999, the phytoplankton biomass and productivity was low in the freshwater-dominated estuary ($<20\,mg\,chl\,m^{-2}$ and $<100\,mg\,C\,m^{-2}\,d^{-1}$, respectively) possibly due to light limitation as a result of dilution/mixing and turbidity (Yin et al., 2004c). Maximal biomass and productivity occurred at the edge of the estuarine coastal plume south of Hong Kong, reaching $70\,mg\,chl\,m^{-2}$ and $4.2\,g\,C\,m^{-2}\,d^{-1}$ with >50% of the biomass in the $>5\,\mu m$ size fraction (mainly diatoms) (Yin et al., 2004c). On July 22–26, the normal SW monsoon winds changed direction and blew from the NE direction and this pushed the estuarine plume further westward, mixed the water column and increased the surface salinity, and a large phytoplankton bloom developed ($52–150\,mg\,chl\,m^{-2}$; and surface Chl was $6–15\,mg\,m^{-3}$) (Yin et al., 2004c). A similar easterly wind event (speed $10\,m\,s^{-1}$) was observed again during July 2000 (Yin et al., 2004c). Therefore, episodic wind events not only change the spatial distribution of the plume, but also sporadic easterly winds can increase the magnitude of the bloom, perhaps by increased retention of the plume in the estuary during its movement out of the estuary (Yin et al., 2004c).

To understand the high-frequency phytoplankton dynamics in coastal waters, a real-time field monitoring system has been developed and successfully tracked 19 algal blooms in the southern and eastern Hong Kong waters (Lee et al., 2005). In the shallow weakly flushed coastal water (depth 7–10 m, tidal current $5–19\,cm\,s^{-1}$), the bloom is short lived, typically lasting a few days to over a week, with chlorophyll and DO concentrations in the range of $20–40\,mg\,m^{-3}$ and $2–15\,g\,m^{-3}$, respectively. Based on the field data and three-dimensional hydrodynamic calculations (Lee et al., 2005), it is demonstrated that vertical mixing is a controlling factor in the occurrence of algal blooms. Given sufficient nutrient availability, the vertical turbulent mixing must be below a threshold level for blooms to develop.

This means that algal blooms are favored in low wind and/or calm waters often associated with strong stratification caused by high river discharge (rainfall). The density stratification can reduce the vertical mixing drastically and prevent mixing of phytoplankton out of the photic zone, thus creating favorable algal growth conditions. For example, the occurrence of hypoxia and the size of the 'dead zone' in the Mississippi River have been found to correlate strongly with high river discharges and strong stratification (Justic et al., 1996). The importance of vertical mixing may also explain why algal blooms are rarely observed in the turbulent tidal currents in nutrient-rich Victoria Harbor (Wong and Lee, 2006). In addition to short-term events, there is also a need to study El Niño events and inter-annual and inter-decadal variations in climate change. Yin et al. (1999) have suggested that El Niño may have been responsible for the massive Hong Kong red tide that occurred in the spring of 1998. The unusually high water temperature at the beginning of 1998 may have resulted in more algal growth compared to other years (Tang et al., 2003; Lee and Qu, 2004).

7. Summary

The PRE exhibits fewer impacts from eutrophication than one would expect, because of:

(a) Physical factors
- Tidal and estuarine gravitational circulations afford enormous dilution of organic pollution loads and high surface nutrients from the river.
- Wind and tidally induced vertical mixing can affect the formation of algal blooms by slowing algal growth due to possible light limitation or mixing algal cells out of the photic zone.
- Surface re-aeration and vertical mixing can help transport oxygen to the bottom waters and reduce hypoxia.
- Summer upwelling and estuarine circulation brings in relatively low-oxygen deep water ($\sim$3–4 mg l^{-1}; Fig. 5) and this may increase the potential for hypoxia when the additional BOD produced by algal growth, sinks into this relatively low-oxygen bottom water. The upwelling and estuarine circulation mixes lower nutrient deep water into the high-nutrient surface waters and this dilutes the potential eutrophication impact of the high-nutrient loads coming from the river (Fig. 4).

(b) Chemical factors
- Low P concentrations in the western and southern waters control the amount of algal biomass produced and the potential occurrence of hypoxia. Hence, the shortage of P relative to N means that not all of the large amount of N in the river can be converted to algal biomass (Fig. 4). Consequently, this surplus N is transported offshore, but we do not know if there are any further potential impacts offshore.

(c) Biological factors and eutrophication impacts
- The main eutrophication-related impacts of concern are excessive algal blooms that could increase hypoxia in the bottom waters when the bloom sinks and decomposes. Episodic occurrences of hypoxia have been reported in western and southern, and northeastern waters of Hong Kong, but no long-term and large-scale hypoxic events have been observed in the outer estuary. However, severe hypoxia occurs upstream of Humen in the winter dry season.

8. Future directions

We need to monitor nutrients, chl, bottom water oxygen, and other parameters at a series of stations during different seasons, and ideally monthly. This is a large estuary and hence this is a large undertaking. If we are to manage the estuary in the future, we must have a watershed budget for various inputs of nutrients and pollutants.

We need more information on: (1) the components of the lower trophic levels such as picoplankton, microzooplankton, mesozooplankton, and the importance of the microbial loop. This information is essential if we are to develop a physical–biological coupled ecosystem model; (2) the fate of the surplus N that is transported offshore, (3) offshore algal blooms (especially summer) at the outer edge of the estuarine plume, (4) seasonal and inter-annual variation in the oxygen concentration in the deep water, and (5) the impact of the occurrence of episodic events such as typhoons.

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