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The influence of late summer typhoons and high river discharge on water quality in Hong Kong waters

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ABSTRACT

A typhoon produces a rapid mixing and flushing event and it can be added to the list of other factors such as shallow water depth, spring tidal mixing, the Pearl River discharge, summer upwelling that make Hong Kong waters relatively resistant to eutrophication impacts. Two typhoons passed over Hong Kong waters and provided an opportunity to document the changes in water quality in late summer 2003. Before the typhoon (Aug 19–20) and during a neap tide, a large algal bloom (>10 μg Chl-*a* L^{-1}) occurred in the stratified southern waters influenced by the Pearl River estuarine waters with high NO_3. However, PO_4 and SiO_4 were drawn down to near limiting concentrations by the large bloom. After the typhoons, Chl-*a* decreased to 2 μg L^{-1} due to vertical mixing and advection. The heavy rainfall and increased river discharge quickly re-set the water column to the usual strong summer stratification in only a few days. As a result, high nutrients in the river discharge stimulated another large algal bloom a few days after the next neap tide when tidal mixing was reduced. In the southern waters, the deeper station showed stronger stratification and lower bottom dissolved oxygen (DO) than the shallower station suggesting that the low DO in the bottom water may have come from offshore transport.

1. Introduction

Typhoons, also known as hurricanes or tropical cyclones, are one of the most catastrophic synoptic events that influence coastal regions. An average of about 30 tropical cyclones form in the western tropical Pacific every year and this area has the highest number of typhoons among all the ocean basins (Chan et al., 2004). Some occur in the smaller sea basin, the South China Sea (SCS), and can pose a threat to the densely populated south China coastal area which is one of the world's coastlines most frequently affected by typhoons (Chan et al., 2004; Leung et al., 2007). Over the last 40 years, there was an average of three annual typhoons landing on the south China coast within 300 km of Hong Kong (HKO, 2003). There is emerging evidence that rising sea surface temperature (SST) could lead to an increase in the intensity of typhoons (Tracy et al., 2006). Some reports have identified a trend that directly links warmer SST over the past 30 years with more frequent and intense tropical cyclones (Webster et al., 2005; Hoyos et al., 2006; Zheng and Tang, 2007) the frequency of typhoons striking the China coast per year may be increasing (Lin et al., 2003; Cao et al., 2007).

Typhoons cause a large-scale disturbance to coastal aquatic and terrestrial ecosystems (Valiela et al., 1998; Paerl et al., 2001, 2006a). In estuaries, extreme wind velocities, storm surges and rainfall can cause intense mixing, alterations to circulation, and even changes to geomorphology (Day et al., 1989). Extensive rainfall induces floodwaters that reduce salinity and increase organic matter and nutrients in the estuary (Mitchell et al., 1997; Zhang et al., 2009). Similar effects were reported in the Taiwan Strait after the passage of typhoons Graff and Herb, although some of the increase in nutrients was due to wind-driven upwelling (Shiah et al., 2000). Typhoons could enhance biomass and change the community structure of phytoplankton (Chang et al., 1996; Zhao et al., 2009) and reduce or enhance primary productivity in coastal waters (Fogel et al., 1999). Recent evidence from satellite data showed that there was on average a 30-fold increase in surface Chl-*a* concentration, accounting for 2–4% of the annual new production of the

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SCS due to the 3-day typhoon, Kai-Tak, passing over the area (Lin et al., 2003). Zheng and Tang (2007) reported that an offshore bloom (4 μg Chl-*a* L^{-1}) occurred along Typhoon Damrey's track (the strongest typhoon over Hainan Island in 32 years), due to an increase in nutrients from mixing and upwelling. The typhoon rain and seaward advection by a typhoon-induced current led to a nearshore increase in Chl-*a* off Hainan Island in the northwest SCS. Paerl et al. (1998) documented the impacts of Atlantic hurricanes on USA's largest lagoonal estuary, Pamlico Sound, North Carolina. They found a cascading set of physical, chemical and ecological impacts after hurricanes, such as strong vertical stratification, bottom water hypoxia, a sustained increase in algal biomass, displacement of many marine organisms and an increase in fish disease (Paerl et al., 1998, 2001, 2006a,b, 2007; Peierls et al., 2003).

Hong Kong is located on the south coast of China and connects to the northern part of the SCS and lies on the eastern side of the Pearl River Estuary (PRE). The Pearl River is the second largest river in China and ranked 13th in the world in terms of discharge volume and forms the PRE which flows into the northern shelf of the SCS (Fig. 1). The annual average discharge of the PRE is approximately 10,500 m^3 s^{-1}, with 20% of the total flow occurring during the dry season in October–March and 80% during the wet season in April–September (Yin et al., 2000; Zhou et al., 2011). In the wet season, the residence times of Hong Kong waters are mainly decreased by high river discharge that increased horizontal water velocities. In Victoria Harbour, the water residence times were 1.5–2.5 days in the wet season, which were 3 times shorter than during the dry season (5–7 days) (Kuang and Lee, 2004; Lee et al., 2006). Hong Kong coastal environments are strongly influenced by three water regimes: estuarine waters from the PRE, oceanic waters from the SCS and coastal waters from the China Coastal Current (Yin, 2003; Harrison et al., 2008). These influences are strongly dependent on two seasonal monsoons. In winter, the northeast monsoon prevails and the coastal waters of Hong Kong are dominated by the China Coastal Current. In summer, the southwest monsoon transports deep continental shelf water landward due to upwelling. The estuarine plume covers a large area in the northern SCS when the Pearl River discharge reaches a maximum in summer (Yin et al., 2004; Lee et al., 2006; Harrison et al., 2008).

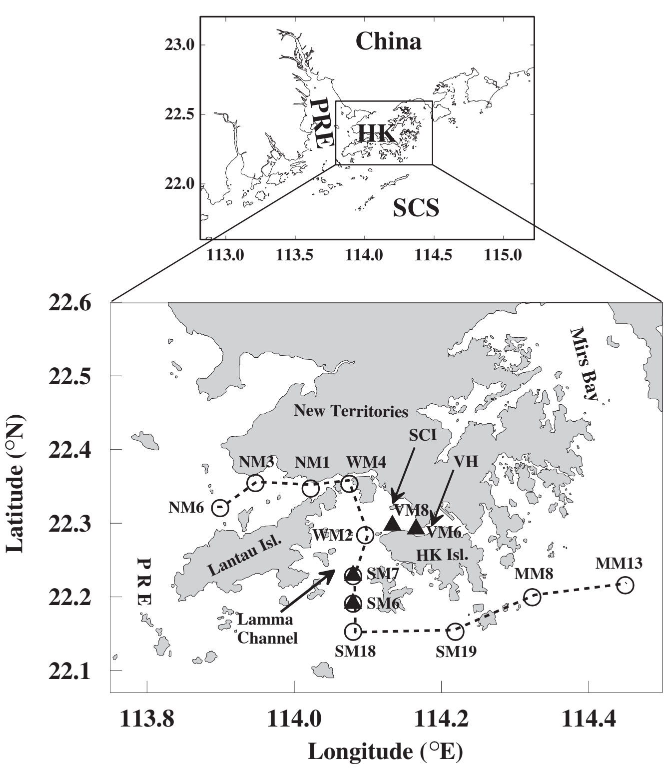

Fig. 1. The map showing a transect (dashed line) of selected EPD routine monitoring stations (open circles) starting from the Pearl River Estuary (PRE) at NM6, through Lamma Channel, to the more oceanic waters of MM13. The 4 filled triangles represent our sampling stations, VM8 and VM6 in Victoria Harbour (VH) and SM7 and SM6 in the southern waters during August to September 2003. HK = Hong Kong; SCI = Stonecutters Island sewage treatment plant; SCS = South China Sea.

The Hong Kong Environmental Protection Department (EPD) implemented a comprehensive temporal and spatial marine water quality monitoring program in 1986 (monthly sampling at 76 stations), which has provided a valuable 21-year long-term dataset for characterizing the eutrophication impacts in Hong Kong waters (EPD, 2006; Lee et al., 2006; Xu et al., 2010a). While this EPD long-term dataset provides excellent seasonal and interannual trends of water quality parameters, there is little information on how short-lived episodic disturbance events such as storms or typhoons induce rapid changes in water quality and influence the environmental assimilative capacity of Hong Kong waters.

Recent studies have shown that estuarine and coastal ecosystems with different hydrodynamics respond differently to climate change, including droughts, storms/hurricanes and floods, with respect to eutrophication susceptibility (Justić et al., 2005; Paerl et al., 2006b; Xu et al., 2010b). This paper tests the hypothesis that episodic wind events, such as a typhoon which brings heavy rain, can quickly re-set the water column and water quality back to the usual summer condition due to the rain-caused rapid increase in run-off and the Pearl River discharge. This response would contribute to making Hong Kong waters relatively resistant to eutrophication impacts such as hypoxia. Two late summer typhoons provided us with an ideal opportunity to evaluate the effect of a typhoon on water quality parameters and eutrophication processes in the PRE. Cruises were conducted during spring and neap tides. We investigated the water column conditions before the typhoons struck, observed a rapid change in nutrients after the typhoon passed, and then the rapid return of water column conditions to pre-typhoon conditions. These field data were used to validate a three-dimensional (3D) hydrodynamic model employed to study the effect of wind speed and direction on the summer tidal circulation and vertical mixing in Hong Kong waters (Kuang et al., 2011).

2. Materials and methods

2.1. Study area

Hong Kong waters are divided into four areas, western waters near the Pearl River estuary, southern and eastern waters and Victoria Harbour (VH). To determine the water quality in VH and western, southern and eastern waters of Hong Kong before (Aug 13) and after (Sept 24) the two typhoons, 11 EPD monitoring stations were chosen along a transect (dashed line in Fig. 1), extending from western waters to Lamma Channel and eastward to more natural coastal waters (Mirs Bay). The western stations (NM6, NM3 and NM1, are 5, 14 and 34 m deep, respectively) are more eutrophic due to the Pearl River estuarine influence. In contrast, the eastern stations (MM8 and MM13, are 31 and 28 m deep, respectively) are more oligotrophic since they are more dominated by coastal/shelf waters from the oligotrophic northern SCS. The southern stations (WM4, WM2, SM7, SM6, SM18 and SM19, are 26, 13, 8, 14, 21, and 24 m deep, respectively) are located in Lamma Channel and influenced by both estuarine and coastal seawater and are often the site of large algal blooms, particularly in summer.

In addition to the EPD monthly sampling, five cruises (C1 to C5) were conducted weekly from Aug 19 to Sept 23, 2003, at two stations in southern waters (SM6, 14 m and SM7, 8 m deep and are referred to as deep and shallow stations, respectively) to examine vertical mixing in shallow vs deep water. The Hong Kong Harbour Area Treatment Scheme (HATS) collects sewage from the densely populated urban areas and conveys the sewage via a 24 km long deep tunnel system to a centralized sewage treatment plant at Stonecutters Island (SCI, Fig. 1), 2 km west of VH. A sewage flow of 1.4 million m^3 d^{-1} after Chemically Enhanced Primary Treatment (CEPT) at SCI was discharged through a 1.2 km long outfall into the area between WM4 and WM2 (Xu et al., 2011). Our field stations were also selected to examine the impact of the HATS sewage outfall. Station VM8 (10 m deep) is located relatively close to the SCI sewage outfall and VM6 is mainly representative of VH, while the two southern stations, SM6 and SM7 are relatively far from the sewage outfall.

2.2. Sampling and hydrographic measurements

Tides in Hong Kong waters are semi-diurnal with a prominent diurnal inequality (Fig. 2). The sampling time during the 5 weekly cruises during Aug–Sep was: cruise 1 (C1), Aug 19–20 (24 h time series, neap tide); C2, Aug 27–28 (24 h time series, spring tide); C3, Sep 9 (sampled twice); C4 on Sep 17 and C5 on Sep 23 were sampled once (Figs. 2 and 3). Data on T, S, nutrients, dissolved oxygen (DO) and Chl-*a* at SM6, SM7, VM6 and VM8 on Aug 13 and Sep 24, 2003, were from the EPD monitoring program.

Vertical profiles of temperature, salinity, depth, pH, DO, Chl-*a* fluorescence and turbidity were measured with a YSI®6600 multi-parameter water quality monitor. Water samples were collected 1 m below the surface and 1 m above the seabed using a 5 L custom-made Plexiglas sampler and stored in 10 L acid-cleaned carboys for sub-sampling.

2.3. Nutrients, DO and chlorophyll analyses

Subsamples for nutrients were taken with a 60 ml syringe and filtered through a pre-combusted 25 mm Whatman GF/F filter mounted on a Swinnex filter holder (Swinnex, Millipore, USA) into 30 ml acid-cleaned Nalgene bottles. The samples were kept frozen until analysis (~2 wks). Nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), orthophosphate (PO_4) and silicate (SiO_4) were determined with a Skalar San Plus Auto-Analyzer following Joint Global Ocean Flux Study (JGOFS) protocols by Knap et al. (1996). Dissolved oxygen (DO) concentration was determined by the Winkler titration method (Knap et al., 1996) using a 716 DMS Titrino Metrohm automated titration instrument. Chl-*a* was extracted in 90% acetone for 24 h in darkness and the fluorescence of the extract was measured with a Turner 10-AU fluorometer (Parsons et al., 1984). Standard methods for sampling and routine water quality measurements were reported by EPD (EPD, 2006) and described by Xu et al. (2010a).

2.4. Wind, rainfall and river discharge data

The daily rainfall from June to September, the monthly total rainfall, the prevailing daily wind speed and direction during August–September, 2003, were obtained from the Waglan Island Automatic Weather Station of the Hong Kong Observatory (HKO), which is located between our sampling stations of SM19 and MM8 (http://www.weather.gov.hk/). Two typhoons, Krovanh (Aug 23–25) and Dujuan (Sep 2–3) sequentially crossed Hong Kong (Fig. 3). During August–September 2003, the total Pearl River discharge was determined from the sum of the discharges from three stations that measure the discharge in the West, North, and East Rivers that eventually flow into the PRE.

3. Results

3.1. Typhoons and wind events

Twenty-three typhoons occurred over the western North Pacific and the SCS in 2003, with five occurring in August and four in September (http://www.weather.gov.hk/wxinfo). Three typhoons passed over Hong Kong's waters (HKO, 2004). On Aug 23, Krovanh moved westward across Luzon Strait and into the northern SCS, causing a Strong Wind Signal No. 3 (according to Hong Kong's

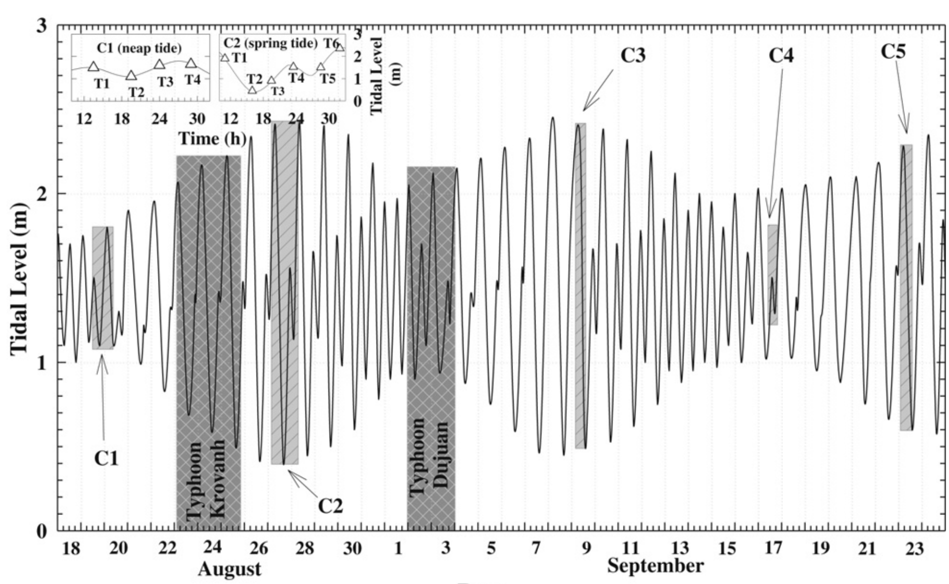

Fig. 2. Tidal cycles during Aug 18 to Sep 23, 2003. The shaded gray box shows the typhoon period for Typhoons Krovanh and Dujuan (▨) during Aug 23–25 and Sep 2–3, and sampling times (cruises 1–5) (▨). The inset figures show the sampling times during the 24 h time series for cruise 1 (C1) during a neap tide and cruise 2 (C2) during a spring tide.

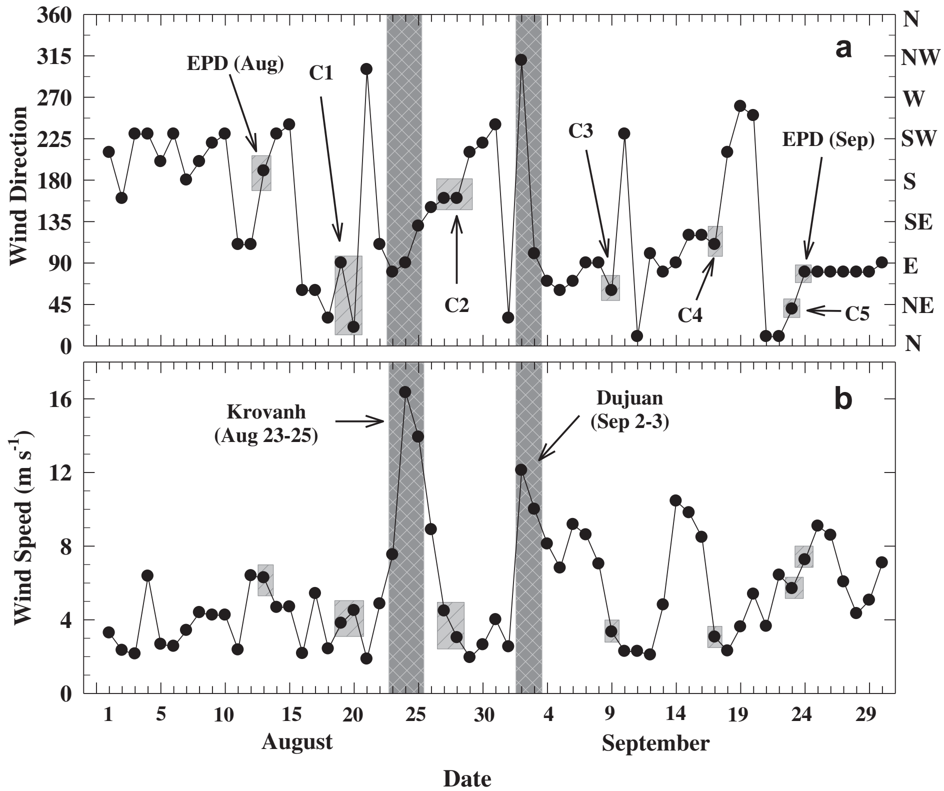

Fig. 3. Daily average wind direction (a) and speed (b) for August–September, 2003. The lighter gray areas ( ) indicate sampling by EPD on Aug 13 and Sept 24. Our 5 cruises were conducted at stations SM6, SM7, VM6 and VM8 on Aug 19–20 (C1), 27–28 (C2) and Sep 9 (C3), 17 (C4), and 23 (C5).

Tropical Cyclone Warning Signals, with a sustained speed of 11–17 m s^{-1}, and gusts >30 m s^{-1}). Dujuan passed 30 km north of Hong Kong and it was the first typhoon since 1999 that necessitated the issuance of the "Increasing Gale or Storm Signal No. 9" (gale or storm force wind is increasing or expected to increase significantly in strength) with occasional heavy rain and severe squalls (http://www.weather.gov.hk; HKO, 2004).

Before Krovanh approached on Aug 23, wind speeds were low with an average of <4 m s^{-1} southwesterly for more than 20 days until Aug 16, and then they switched to more easterly throughout most of September (Fig. 3a). During August–September 2003, the daily average wind speed was 5.5 m s^{-1}, with a much higher average speed of 6 m s^{-1} during our sampling period from Aug 19 to Sep 23 (Fig. 3b). Average wind speeds recorded by HKO were 16 and 12 m s^{-1}, respectively, when Krovanh and Dujuan passed by Hong Kong. Strong winds (>8 m s^{-1}) blew for 2–3 days every week in September after the two typhoon events. A change in the monsoonal wind direction from the normal S/SW to E occurred during Aug 15–20. The east winds blew several days in September (Fig. 3a) and pushed the estuarine plume westward away from Hong Kong.

3.2. Pre-typhoon conditions

The seasonal rainfall during 2003 was 37, 372, 1042 and 493 mm in winter, spring, summer and fall respectively (Fig. 4b). The rainfall in July was abnormally low (only 102 mm) and much lower than June, August and September. The monthly rainfall was 6 and 30% above normal (30 years) for August and September, respectively. The total rainfall during the period of our 5 weekly cruises from Aug 19 to Sep 23 (36 days) was 667 mm, accounting for almost two-thirds of the total rainfall during summer 2003 (Fig. 4a). The heavy rain caused by Krovanh and Dujuan increased the normal daily Pearl River discharge by 50% and reached $>12 \times 10^3$ m^3 s^{-1}.

Due to the high rainfall in June and southwesterly winds, the Pearl River estuarine plume almost reached the eastern waters (MM8 and MM13) and it resulted in strong stratification. The riverine plume had higher concentrations of NO_3, SiO_4, PO_4 and NH_4 than eastern waters (Fig. 5) and bottom nutrient concentrations were much less than the estuarine coastal plume at the surface. Chl-*a* was low (<3 μg L^{-1}) in June, especially in the southern and eastern waters. Bottom DO reached near hypoxic levels (~2 mg L^{-1}) at WM4 near the HATS sewage outfall site. The water column was stratified on June 18 and July 28 as indicated by differences in salinity between surface and bottom. The stratification was stronger in the western water (NM1, NM3 and NM6) and at WM2 and WM4 than other stations (Fig. 5). Surface turbidity was mostly near or lower than 5 NTU along the transect from western to eastern waters in June and July, except in the western waters in June which ranged from 5 to 10 NTU. A large algal bloom (~20 μg Chl-*a* L^{-1}) developed in the southern waters, especially at WM4 and WM2 and bottom DO was still near hypoxic levels at WM4. Upwelling occurred in the eastern waters as indicated by the colder and generally more saline bottom water in July than in June (Fig. 5).

On August 13, one week before the first typhoon during a neap tide, stratification was weaker than on July 28, while it was still evident in the eastern waters. A large bloom occurred in southern waters and in particular, the bloom extended to near the bottom at SM7 and WM2 with a turbidity of <10 NTU (Fig. 6). NO_3 and SiO_4 concentrations decreased to near limiting concentrations at SM7 and in eastern waters (Fig. 6). Relative to other stations, bottom DO was low in most southern waters, except at the shallow SM7 station.

3.3. Response to typhoons: Victoria Harbour

On August 19–20 (C1), five days before Krovanh and during a neap tide at two stations in VH, there was relatively weak

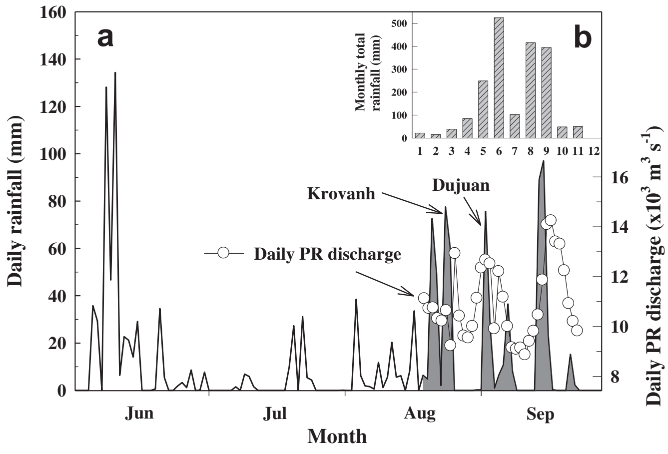

Fig. 4. a) Daily rainfall (mm) from June to September and Pearl River discharge ($\times10^3$ m^3 s^{-1}) during sampling time, and (b) monthly total rainfall for 2003 (data from the Hong Kong Observatory). The gray area in (a) is the daily rainfall during the 5 cruises from Aug 19 to Sep 23. The second and third gray areas in Aug 23–25 and Sep 2–3 are for Typhoons Krovanh and Dujuan, respectively.

stratification with relatively low but saturating nutrient concentrations (Fig. 7). NH_4 and PO_4 were higher at VM6 in the middle of VH than at VM8 on the west side of the harbour near the local sewage inputs. Very high ambient DIN/PO_4 (94 at surface and 71 at bottom) and DIN/SiO_4 (17 at surface and 9 at bottom) ratios indicated potential P and Si limitation. Chl-*a* was high (~ 10 μg L^{-1}) and bottom DO ranged from 4 to 6 mg L^{-1} (Fig. 7).

Three days after the first typhoon (Aug 23–25 during C2) and during a spring tide, there was still haline stratification probably due to rainfall and land runoff (Fig. 7). Chl-*a* decreased to <1.5 μg L^{-1} and nutrients almost doubled, especially with NO_3 being higher at VM8 than at VM6. There was a significant increase in bottom DO, a decrease in the DIN/PO_4 and DIN/SiO_4 ratios and Chl-*a* (Fig. 7).

Dujuan (Sep 2–3) had winds of 10–12 m s^{-1} and blew for nearly 1 week (Fig. 3). One week after Dujuan (Sep 9; C3) when winds decreased to <4 m s^{-1} and during a spring tide, there was little stratification and nutrients and bottom DO remained at similar levels as at C2, and Chl-*a* was still very low (Fig. 7).

Three days after another strong wind event (~ 10 m s^{-1}) on Sep 14–15 (C4) and during a neap tide, stratification strengthened and Chl-*a* started to increase (Fig. 7). By Sep 23 and 24 (C5) during a post-neap tide with low winds, Chl-*a* increased to >5 μg L^{-1} with a subsequent decrease in nutrients during this 5 day period.

3.4. Response to typhoons: southern waters

On Aug 19–20 during C1, 5 days before Krovanh during a neap tide and low winds, there was strong stratification, especially at the deep station (SM6). An algal bloom developed, consuming nutrients to low levels at both the shallow and deep stations (Fig. 8). At the deep station (SM6), the surface Chl-*a* was lower than the shallow station (SM7), but there was a large Chl-*a* maximum at depth (Figs. 9 and 10). DO was lower in the bottom water at the deep station than at the shallow station, possibly due to respiration in the Chl-*a* maximum layer (Figs. 9 and 10).

On Aug 23–25, after Krovanh during C2 and a spring tide, high vertical mixing due to the typhoon winds was down to ~8 m (Figs. 9 and 10), and there was a reduction in Chl-*a* and an almost 3-fold increase in most nutrients with a larger increase in NO_3 at the shallow station (Fig. 8). There was a larger variation in surface salinity at both the shallow and deep stations, indicating that strong haline-driven stratification due to high river discharge formed quickly after the typhoon event (Figs. 9 and 10). Bottom water DO was replenished by the vertical mixing and Chl-*a* was low and relatively evenly distributed in the water column (Figs. 9 and 10).

Dujuan struck on Sep 2–3 and after one week of continuous high winds, Chl-*a* remained low and nutrients were high on Sep 9 (C3). At the end of the ebb tide at the deep station, surface temperature was higher and salinity and DO were lower than the late flood tide, probably due to the discharge from the Pearl River during the ebb tide (Figs. 9 and 10). It was only after an additional week of low winds and a late neap tide that a large algal bloom (20 μg Chl-*a* L^{-1}) occurred with a drawdown of nutrients on Sep 23 (C5). The bloom was larger at the shallow station and it was possibly limited by Si (Fig. 8).

As a result of the decrease in Chl-*a*, DO consumption was also reduced after the typhoon. DO consumption was almost 1.03 mg L^{-1} per day before the typhoon, but it decreased significantly to 0.53 mg L^{-1} per day after the typhoon in the bottom water of the deep station at SM6 (data not shown). In the former case, it would take only 3.4 days to consume the in-situ DO (5.6 mg L^{-1}) to the hypoxic level (2 mg L^{-1}) and this could explain the occurrence of hypoxia during some phases of the tidal cycle before the typhoon. However, after the typhoon, bacterial respiration measurements indicated that it would take about 8.8 days to reduce the bottom DO (6.6 mg L^{-1}) to the hypoxic level.

4. Discussion

Water quality and eutrophication impacts in Hong Kong waters are influenced by high nutrient inputs from the Pearl River estuary, local Hong Kong sewage and the invasion and mixing with more oligotrophic coastal/oceanic northern SCS waters (Yin and Harrison, 2007; Harrison et al., 2008). The hydrography of Hong Kong waters is closely related to the salinity structure of the coastal waters, which is a mixture of Pearl River freshwater discharge and high salinity oceanic shelf water, and mainly influenced by three factors: tidal currents, the Pearl River discharge, and monsoon-induced coastal current (Watts, 1973; Kuang et al., 2011). The winter dry season NE monsoon winds produce downwelling, while the summer wet season SW monsoon induces upwelling which serves as a flushing mechanism to reduce severe eutrophication impacts (Yin, 2003; Yin et al., 2004). Episodic events such as typhoons, can produce large changes on water circulation and water column mixing/stratification. Inputs of nutrients also increase due to hurricanes and these changes can bring severe eutrophication impacts to some estuarine ecosystems such as Pamlico Sound, North Carolina (Paerl et al., 1998, 2001, 2006a,b, 2007; Peierls et al., 2003). Even though several typhoons occur every summer, their effect on water quality has not been systematically investigated for Hong Kong waters.

4.1. Pre-typhoon conditions

The summer rainy season and the SW monsoon drive the Pearl River estuarine plume into western and southern waters of Hong Kong and the estuarine influence almost reached the outer eastern waters as shown by the surface salinity (Figs. 5 and 6). This resulted in typical gradients in water quality across the estuarine plume and coastal waters which agrees with observations by Yin and Harrison (2007) and Zhou et al. (2011). The accompanying haline-induced stratification with high nutrients and adequate light set up ideal conditions for the formation of algal blooms. On a temporal basis, July and August appear to be the most favorable months for large algal blooms and low oxygen bottom water, while spatially,

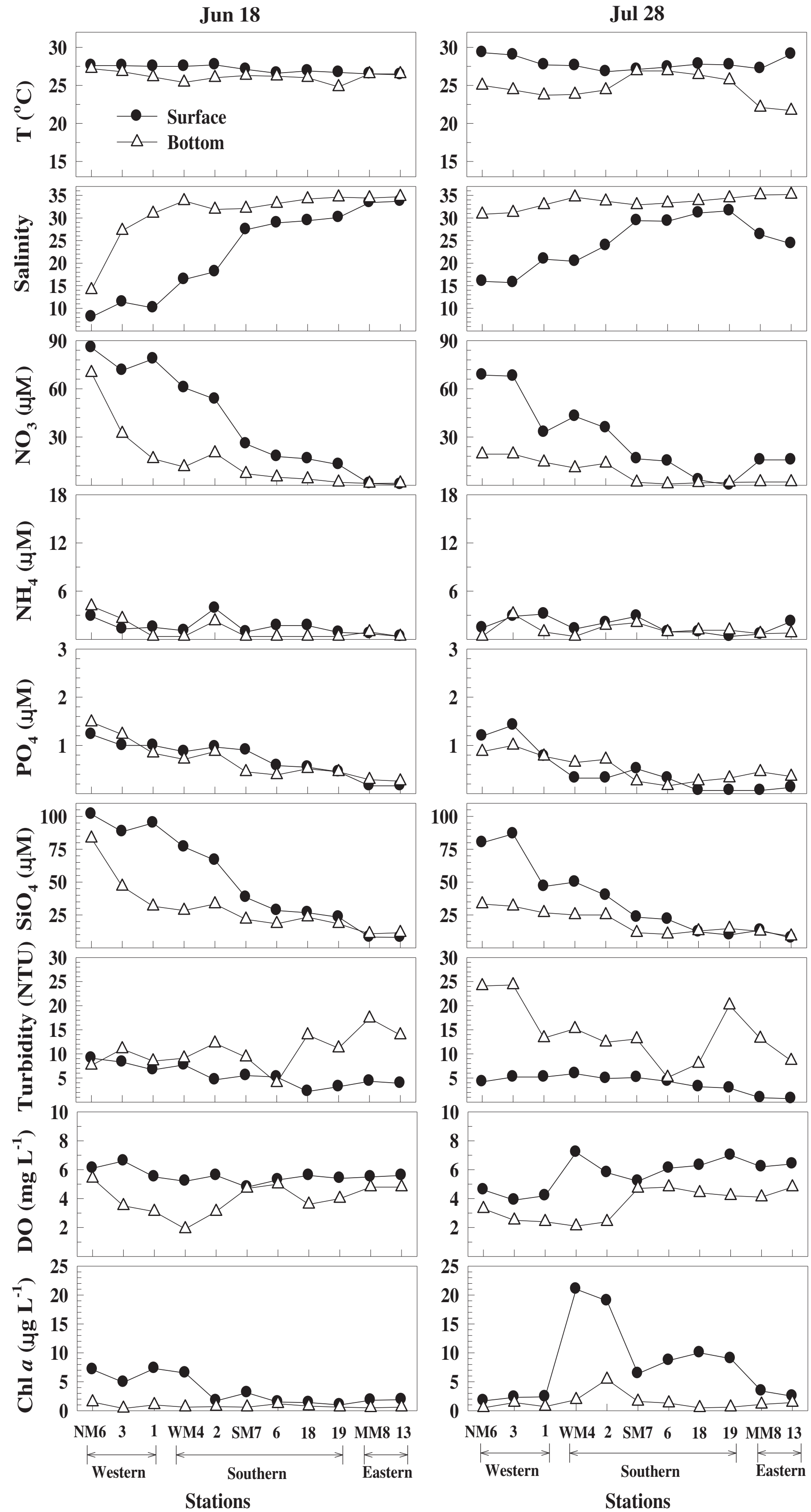

Fig. 5. Environmental conditions on June 18 and July 28 well before the occurrence of the two typhoons in Aug–Sep. Temperature (*T*), salinity, NO_3, NH_4, PO_4, SiO_4, turbidity, DO and Chl-*a* at the surface and bottom for each station along the transect shown in Fig. 1.

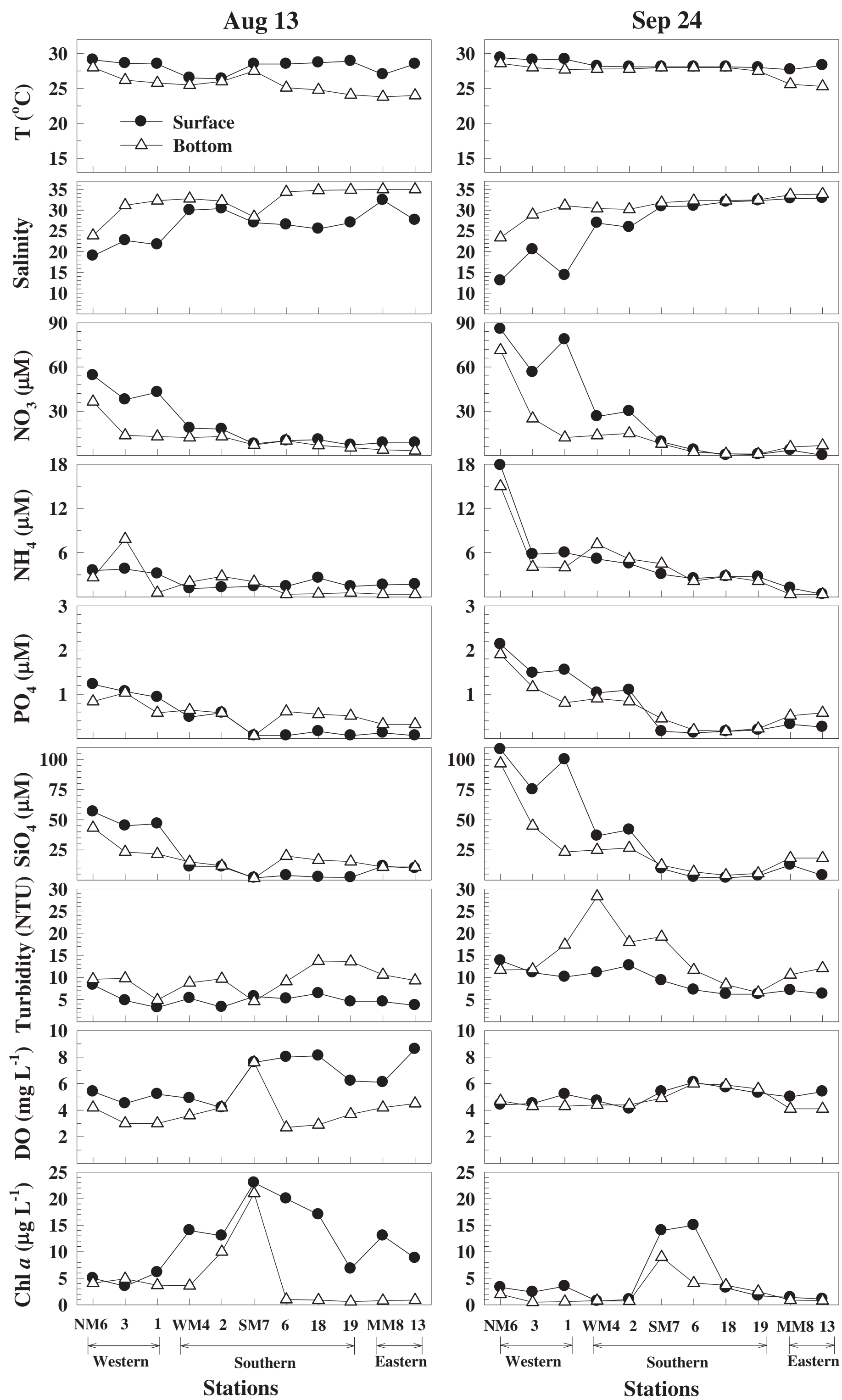

Fig. 6. Environmental conditions on Aug 13 and Sep 24 just before and after the typhoons. Temperature (*T*), salinity, NO_3, NH_4, PO_4, SiO_4, turbidity, DO and Chl-*a* at the surface and bottom for each station along the transect shown in Fig. 1.

southern waters represent the estuarine coastal frontal area which favors the development of algal blooms. Yin et al. (2000) also found the highest algal biomass in southern waters between Lantau Island and Hong Kong Island.

The Pearl River estuarine water brought high nutrients into the west side of Hong Kong. High NO_3, SiO_4 and PO_4 were significantly correlated with low salinity along the transect in the wet season at estuarine stations, NW6, NW3 and NW1 (Figs. 5 and 6). The weak correlation between salinity and NH_4 indicated that NH_4 in the Pearl River disappeared faster than NO_3 probably due to preferential utilization of NH_4 over NO_3 by phytoplankton (Xu et al., 2012) and probably nitrification processes. The higher NH_4 and PO_4 in VH

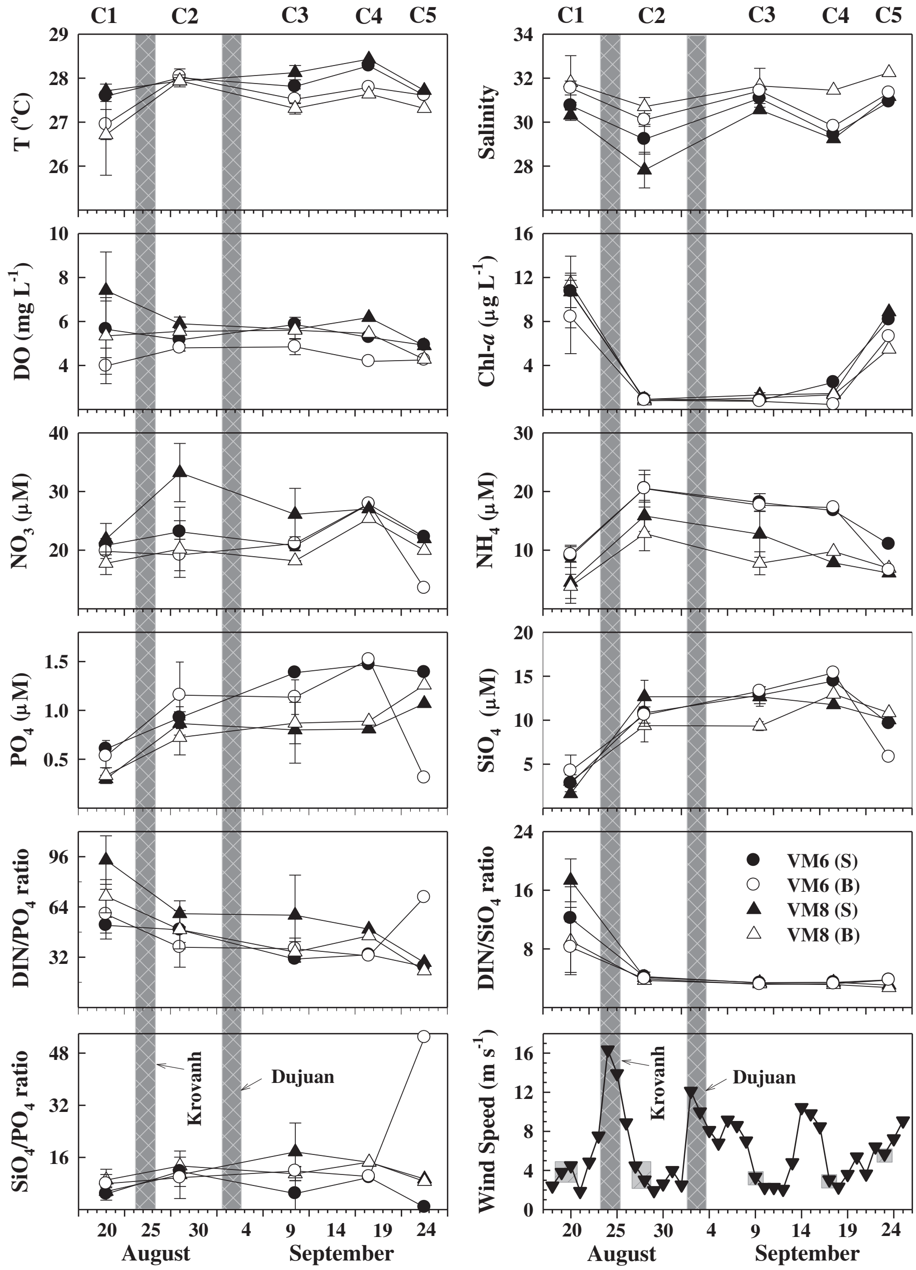

Fig. 7. Water quality changes at VM6 and VM8 in Victoria Harbour for 5 cruises during August to September 2003. The circles and triangles represent parameters for VM6 and VM8, respectively. Solid symbols are for the surface (S) and open symbols are for the bottom (B).

at stations VM8 and VM6 and WM2 were mainly from the local sewage effluent (Fig. 7) as demonstrated by Yin and Harrison (2007).

The large algal bloom and low bottom oxygen that developed near the HATS sewage discharge site (WM2 and WM4) might be related to sewage inputs under strong stratification, but surface currents are quite high in this area and advection is strong. By Aug 13 during a neap tide, the position of the bloom moved southward in the offshore direction at the shallow (8 m) SM7 station (Fig. 6). The 25 μg Chl-*a* L^{-1} bloom extended to the bottom, probably due to moderate wind ($\sim$7 m s^{-1}) and tidal mixing which eliminated stratification and low PO_4 and SiO_4 probably limited the biomass of the bloom (Fig. 6). By microscopical analysis after the cruises, we found the blooms were dominated by fast growing chain-forming diatoms such as *Skeletonema*, *Chaetoceros* and *Thalassiosira*, and this can help to explain the role of Si limitation. These same diatom genera also dominated the diatom composition which made up >90% of the phytoplankton abundance at the same sites in other summer cruises (Xu et al., 2009; Ho et al., 2010).

In this coastal ecosystem, water depth is one of the key factors that influences the ecosystem buffering capacity and the extent of stratification (Lee et al., 2006; Kuang et al., 2011). In deep areas such as SM6, stratification was stronger than at the shallower station (SM7) during C1 before the typhoon (Figs. 9 and 10). As a result, bottom DO at SM6 episodically reached hypoxic conditions (DO < 2 mg L^{-1}), while DO at SM7 was <4 mg L^{-1}. This suggests that the low DO bottom water may be coming from offshore coastal waters. The change from SW to easterly winds from Aug 16 would tend to push the Pearl River plume away from Hong Kong waters resulting in a stronger intrusion of more saline coastal/oceanic waters into Hong Kong coastal waters, as observed by Yin et al. (2004) and simulated in a model by Kuang et al. (2011).

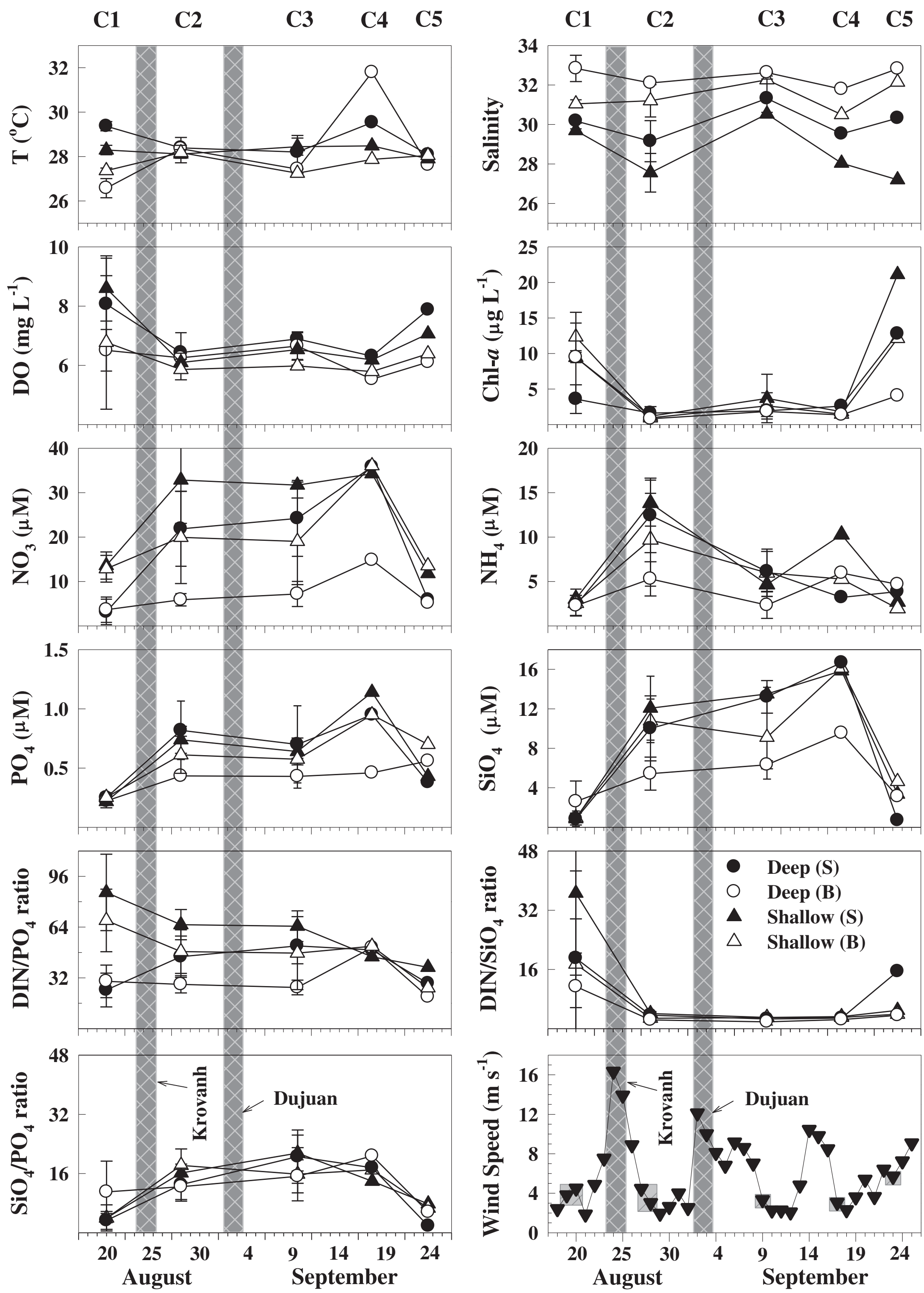

Fig. 8. Same as Fig. 7, except at SM6 (deep) and SM7 (shallow) in southern waters for 5 cruises during August to September 2003.

Therefore, the deeper SM6 station was influenced more by poor DO coastal waters with much higher salinity and lower DO than the shallower SM7 station (Figs. 9 and 10).

4.2. Response to typhoons

Using a calibrated 3D hydrodynamic model, Kuang et al. (2011) modeled the relationship between wind events and the physical hydrography of Hong Kong waters. They demonstrated that the water column can only be vertically well mixed after a strong NE wind (10 m s^{-1}) blows for 5 days, but not for a 5 or 7.5 m s^{-1} wind. Their model results agree well with the observation that the strong SE wind induced by Typhoon Krovanh during August 23–26 strongly mixed the water column.

Since VH always has a higher degree of mixing than southern waters (Yin and Harrison, 2007), the mixing effects of the typhoons

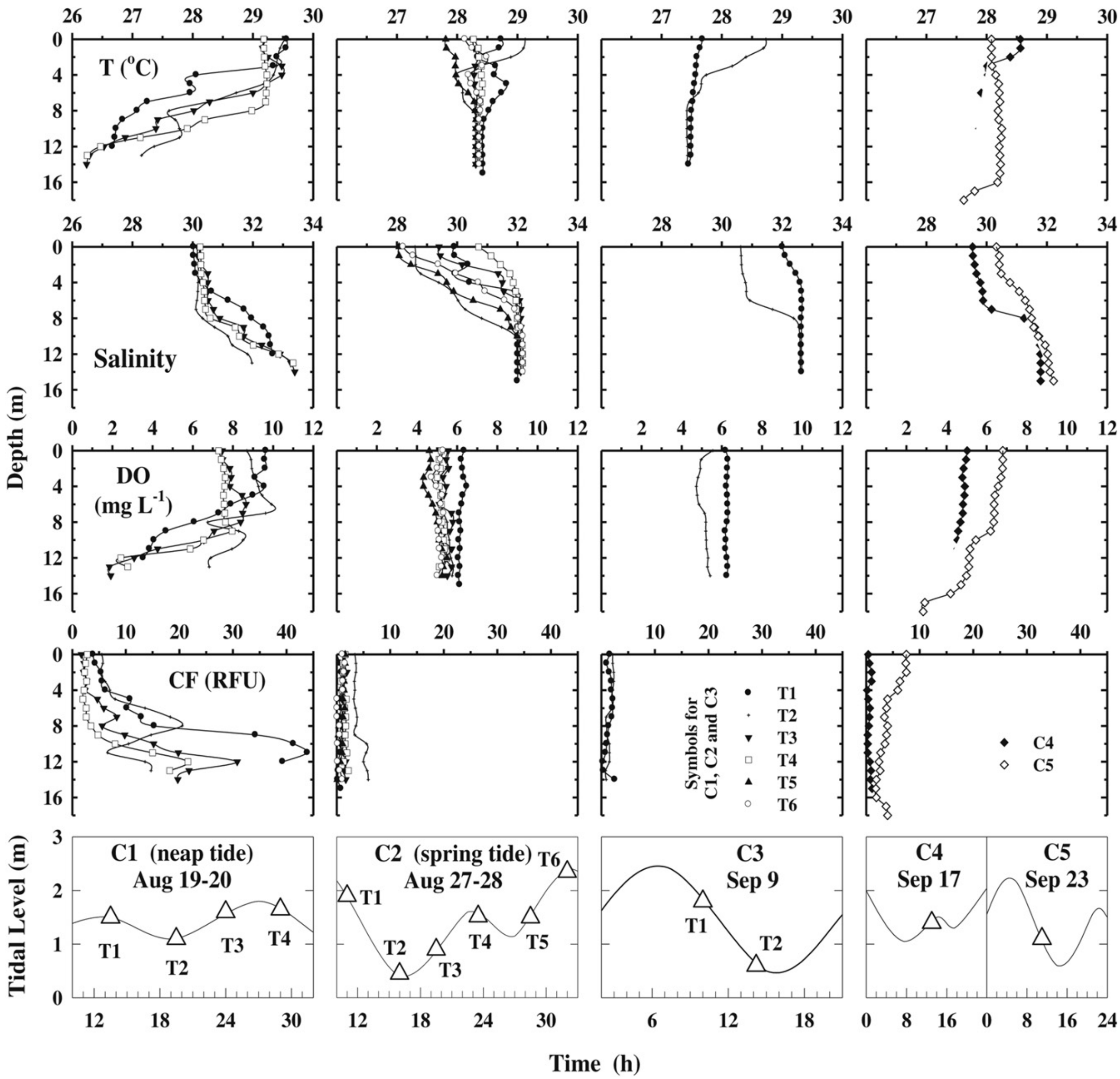

Fig. 9. Vertical profiles of temperature (*T*), salinity, dissolved oxygen (DO) and chlorophyll fluorescence (CF), relative fluorescence unit (RFU) at Stn SM6 (deep) for 5 cruises during ebb and flood and spring and neap tides (see tidal cycles) for August to September 2003.

were more visible in southern waters. Three days after the first typhoon, there was a strong salinity gradient between the surface and bottom, indicating a quick recovery of stratification due to the increased Pearl River outflow. The typhoon mixed and flushed out the pre-typhoon algal bloom and Chl-*a* dropped to <2 μg L^{-1} (Fig. 11), but there was only a small change in bottom DO (Figs. 7 and 8).

The amount of N from HATS is about 25% of the PR discharge in summer (Xu et al., 2011, 2012). The quantity of nutrients from SCI was relatively constant and the increasing discharge induced by heavy typhoon rainfall was responsible for part of the increase in nutrients. The surface waters showed significantly elevated NO_3 and SiO_4 from the river discharge and elevated surface and bottom NH_4 and PO_4. The second typhoon had similar effects as the first typhoon on the water quality. DIN/PO_4 and DIN/SiO_4 ratios increased which set up the system for potential P limitation, or P and Si co-limitation when the next algal (diatom) bloom occurred. This was exactly the case on Aug 13 at SM7 when both P and Si were low and appeared to be co-limiting (Fig. 6). Three weeks after the typhoons at SM6 and SM7, Si again reached limiting concentrations and was even lower than PO_4 during the large bloom (15–20 μg Chl-*a* L^{-1}) on Sept 23 (Fig. 8). Therefore, the effects of typhoons on water quality and algal blooms were relatively short-lived, as the water quality conditions returned to the previous conditions (Aug 13) a few days after Typhoon Dujuan. As a result, an algal bloom occurred in southern waters and VH (Figs. 7, 8 and 11). This is in contrast to Pamlico Sound, North Carolina, which is almost enclosed with a long residence time. Three sequential typhoons injected large amounts of nutrients from the sediments into the water column and this increased the Chl-*a* and changed the phytoplankton community structure to a dominance by green microalgae (Paerl et al., 1998). The effects of these 3 sequential

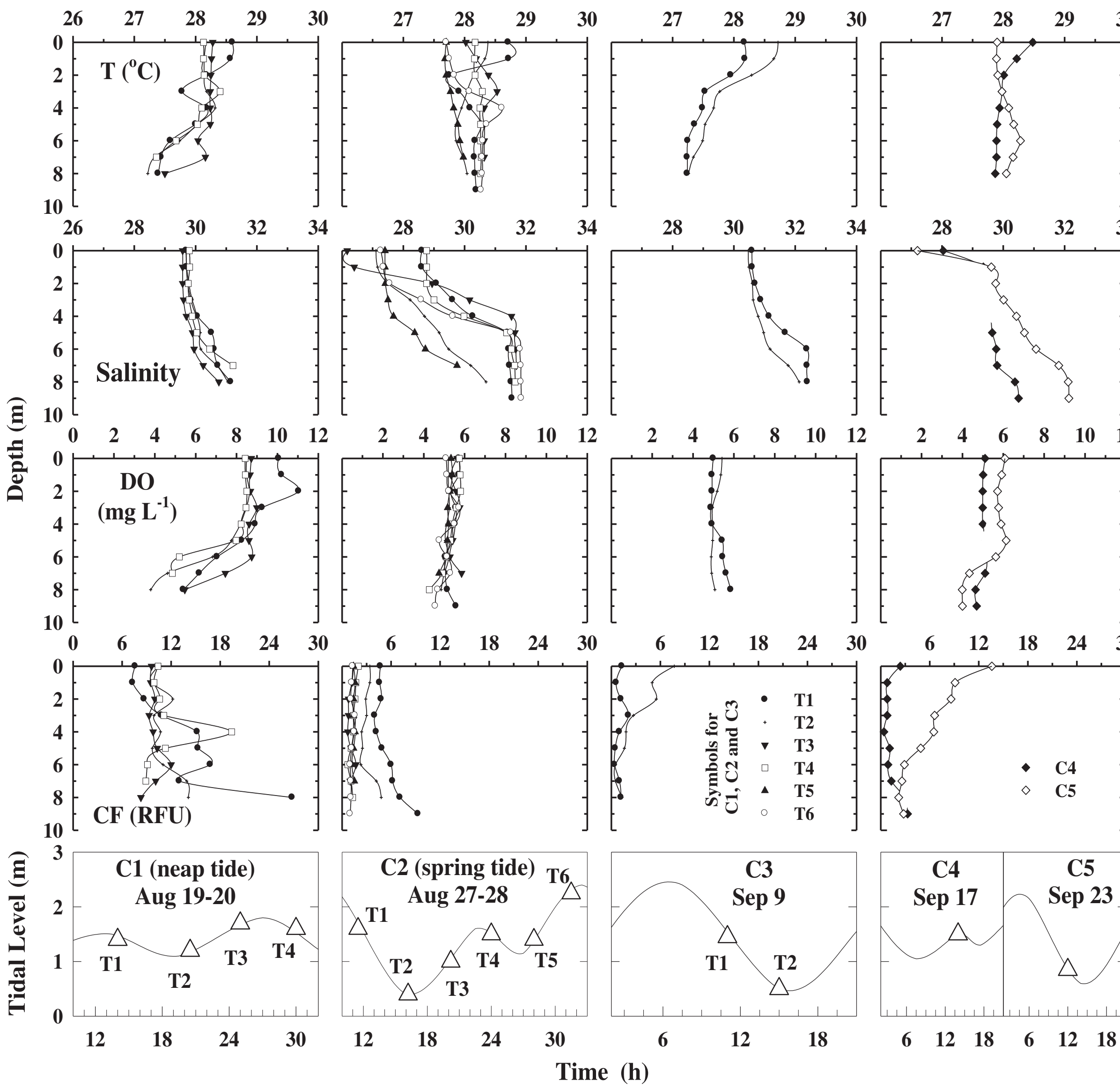

Fig. 10. Vertical profiles of temperature (*T*), salinity, dissolved oxygen (DO) and chlorophyll fluorescence (CF), relative fluorescence unit (RFU) at Stn SM7 (shallow) for 5 cruises during ebb and flood and spring and neap tides (see tidal cycles) for August to September 2003.

hurricanes lasted for up to six months. Vertical mixing is a common nutrient injection process during typhoons (Lin et al., 2003; Zhang et al., 2009; Zhao et al., 2009). Higher phytoplankton biomass fueled by upwelling-induced nutrients during the passage of a typhoon has been observed in the Gulf of Mexico (Walker et al., 2005) and in the nearshore and offshore areas of the SCS (Lin et al., 2003; Zheng and Tang, 2007; Zhao et al., 2009).

Enhanced nutrient input coupled with increased runoff as a result of rainfall associated with Hurricane Katrina was studied by Zhang et al. (2009) in Biscayne Bay, Florida. However, the effect of typhoon/tropical cyclones on water quality in coastal bays depends on the different attributes of individual storms and bays (Paerl et al., 2001, 2006a; Mallin and Corbett, 2006; Zhang et al., 2009). Some other coastal water systems, such as the Pamlico Sound system, North Carolina (which drains to the Atlantic Ocean via three narrow passages) have a relatively long water residence time approximately one year (Paerl et al., 2007). In contrast, Hong Kong waters are quickly flushed by high river discharge in the wet season with a water residence time of 1.5–2.5 days (Lee et al., 2006).

The strong vertical mixing and flushing effect of the typhoons interrupted the formation of hypoxia since the algal bloom was mixed downwards from the photic zone, and was diluted, dispersed

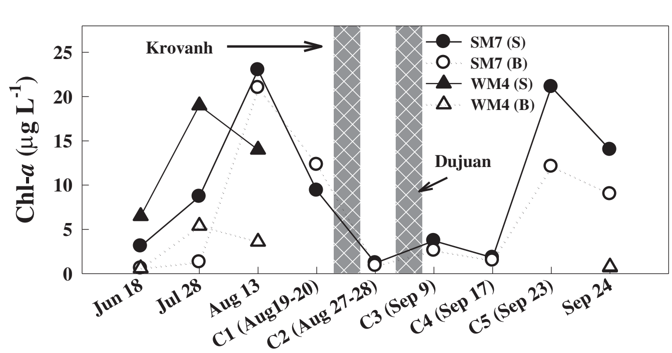

Fig. 11. Temporal changes in Chl-*a* at WM4 and SM7 on Jun 18, Jul 28, Aug 13 and Sep 24 (from EPD) and our 5 cruises (C1–C5) before and after 2 Typhoons Krovanh and Dujuan. Solid symbols are for the surface (S) and open symbols are for the bottom (B).

and probably transported to offshore coastal waters during the typhoon event (Harrison et al., 2008). This offshore transport of algal biomass and presumably some sinking to depth, could contribute organic matter to the deep water further offshore. After the typhoon, the typical two-layer stratified flow circulation returned, with the estuarine coastal plume flowing seaward at the surface and the bottom oceanic water layer moving onshore (Yin, 2003). The southwest monsoonal winds strengthened this estuarine circulation. As a result, relatively low DO bottom water moved onshore again after the typhoon. With the addition of organic matter from algal blooms, it would not take long for DO to be consumed to hypoxic levels. The low bottom DO water was indeed observed at the deeper station SM6 on Sep 23 (Fig. 9). The mechanisms that explain these episodic bottom water low oxygen events is under investigation. The processes were consistent with the similar conceptual model as described in Yin et al. (2010). They concluded that the drivers that regulated the phytoplankton biomass/blooms in estuarine waters and semi-enclosed bays were light penetration (turbidity), nutrient limitation (nutrient ratios), water stratification (stability), residence time (exchange) and climate variability (such as typhoon events).

5. Summary

During the typhoon, Chl-*a* decreased due to strong wind-induced vertical mixing, dilution and rapid flushing. Due to the heavy rainfall delivered by the typhoons, the increase in the Pearl River discharge quickly re-set the typical summer stratification. The river discharge flooded the area with high nitrogen and set up the system for a return to P and Si limitation when a new algal (diatom) bloom was produced a few days after the typhoon when vertical mixing in the water column was reduced. Therefore, the mixing and dilution effects of typhoons are relatively short-lived in coastal ecosystems that are dominated by high river discharge since haline stratification is set up again in a few days.

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