Deep-Sea Research II 117 (2015) 3–9

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Introduction

The oceanography of the *No*rthern *so*uth China Sea *S*helf-Sea (NoSoCS) and its adjacent Waters—overview and Highlights[1]

ARTICLE INFO

Keywords:
South China Sea
Shelf-sea
Nutrients
Internal waves
Shelf circulation
Upwelling

ABSTRACT

Tropical shelf-Seas constitute a sub-set of shelf-seas that has not been studied extensively. The *No*rthern *S*outh China Sea *S*helf-sea (NoSoCS) study is a continuation of the longstanding interest in Taiwan on the oceanography of the East Asian shelf-seas, and is an attempt to provide systematic and synoptic observations on a tropical shelf-sea. The two basic hypotheses in the study are: (1) as in the Ocean interior, the behaviors of the shelf-seas vary with latitude; and (2) the behaviors of the NoSoCS are representative of those of the shelf-seas in the tropical zone. The NoSoCS has been sampled bi-annually in alternating seasons since 2009. The results obtained primarily in 2009 to 2012 are presented here. As in the tropical Ocean interior, a distinguishing characteristic of the NoSoCS is its shallow mixed layer, with depths of about 40 m in the summer and 70 m in the winter. As similar mixed layer depths are found in the adjoining Northern South China Sea (SCS) and they are shallower than the shelf break depth of 120 m, the upper nutricline Water in the Northern SCS extends freely into the NoSoCS and forms a layer of Water with significant concentrations of the nutrients immediately below its mixed layer. Any process that can induce vertical mixing on the shelf may make the nutrients in this subsurface Water available for supporting biological activities in the mixed layer in the NoSoCS. Such processes include winter convective overturn over the entire NoSoCS as a result of surface cooling and the strong northeast monsoonal wind, winter formation of bottom Water in parts of the inner and middle shelf, the action of internal waves at the outer shelf and the continental slope, and upwelling maintained by wind and/or topography. The upwelling takes place in the summer off the coasts of Dongshan–Shantou and the northeast coasts of the Hainan Island, but year-round at the Taiwan Bank. Upwelling over the shelf break is not required for bringing the nutrients in the sub-surface Waters in the open SCS to the NoSoCS, and it was not observed. In addition to vertical mixing, terrestrial inputs, especially through the outflow of the Pearl River, which reaches its peak in the summer, also contribute to the spatial and temporal variations in the composition of the NoSoCS. The combined effects of all these processes lead to a unique seasonal pattern in the variations of the surface concentrations of chlorophyll-a in the NoSoCS, with two distinct yearly maxima in the winter and summer.

1. Introduction—shelf-seas and the Northern south China Sea Shelf-Sea (NoSoCS) study

Continental shelves of various widths rim the Oceans (Postma and Zijlstra, 1988; Walsh, 1988). The Waters that extend from the coasts to the shelf-break on those shelves with sufficient widths form the shelf-seas. These Seas are the part of the Ocean that is at the closest proximity to land, and are thus most sensitive to the effects of the ever-increasing human activities. They also constitute an integral component of the continental margin, which plays a disproportionately important role, relative to their areal coverage, in regulating the biogeochemical behaviors of the Oceans (Liu et al., 2010). Thus, ecologically, while shelf-seas constitute only about 7% of the area of the global Ocean, they support about one-fifth of marine primary production and half of global fish production (Ryther, 1969). Geochemically, their high biological activities, high particulate and organic loads, and high sediment-surface to Water-volume ratio favor the occurrence of many of the principal types of biogeochemical reactions, such as acid–base, oxidation–reduction, complexation, photochemical and adsorption–desorption reactions. For example, the shelf-seas' lower concentrations of iodate and higher concentrations of iodide relative to the open Ocean have been explained by the biologically mediated reduction of iodate to iodide in the shelf (Wong, 1995; Wong et al., 2004). The higher concentrations of hydrogen peroxide have been attributed to the facilitation of its photochemical production by the ready availability of organic chromophores in the shelf Waters (Moore et al., 1993). The elevated concentrations of manganese (Wei et al., 2001) and methane (Brooks et al., 1981) have been linked to a sedimentary source, while the depletion of ^{210}Pb (Nozaki et al., 1976) may have resulted from a sedimentary

---

[1] Deep-Sea Research II: Special Issue on "Oceanography of the *No*rthern *S*outh China Sea *S*helf-sea (NoSoCS) and its Adjacent Waters".

http://dx.doi.org/10.1016/j.dsr2.2015.04.026
0967-0645/

sink and the interactions between the dissolved and particulate phases in the Water column. More recently, the acidification of coastal sub-surface Waters has been attributed partially to eutrophication (Cai et al., 2011). These reactions modulate the material supplies to the shelf-seas from terrestrial and open-Ocean sources and help to determine the net chemical fluxes in mass exchanges between the shelf-seas and the open Ocean (Wong 1995). Recent discussions on the regulation of the global carbon cycle and its ramifications on the concentration of atmospheric CO_2 have also amply demonstrated the importance of the shelf-seas as a biogeochemical province (USGOFS, 1987; JGOFS, 1992; Buddemeier et al., 2002; SOLAS, 2004; IMBER, 2005; IPCC, 2007). Thus, Tsunogai et al. (1999) hypothesized that the shelf-seas may be especially effective in the removal of atmospheric CO_2 through the “continental shelf pump”. Thomas et al. (2004) proposed that the shelf-seas may account for 20% of the world Ocean's uptake of anthropogenic CO_2. Mckenzie (2010) suggested that the continental margin, which includes the continental slope and rise in addition to the shelf, may account for as much as 50% of the biological pump for the transfer of organic carbon to—and thus sequestration of carbon in—the deep Sea, and a minimum of 15% of the net transfer of atmospheric CO_2 to the Oceans. Liu et al. (2000) suggested that three-quarters of the carbon burial in the Oceans may occur on continental margins.

To date, most of the shelf-seas that have been studied extensively and systematically are located in the temperate zone, such as the Baltic Sea-North Sea, the Bay of Biscay, the Texas-Louisiana shelf, the South Atlantic Bight, the Middle Atlantic Bight, the California-Washington shelf, and the East China Sea shelf-sea (Liu et al., 2010). Since the average behaviors of the shelf-seas and their contribution to the global picture have been extrapolated primarily from the observations in these shelf seas, these averages implicitly assume that the temperate shelf-seas are representative of all the shelf-seas. Recent studies challenge the veracity of this assumption and propose that, in order to make room for the possible diverse behaviors that may be found in them, shelf-seas should be subdivided into sub-groups and the average behavior of the shelf-seas should be derived from some statistical combination of these subgroups (Cai and Dai, 2004; Borges, 2005; Borges et al., 2005; Cai et al., 2006).

Conventionally, the Oceans have been sub-divided into the polar, temperate and tropical Oceans and the behaviors of the Oceans in these sub-regions are indeed distinct from each other (Heinrich, 1962). A tally of shelf-seas at 60–90°, 30–60° and 0–30° (Walsh, 1988), which represent approximately the polar, temperate and tropical shelf-seas respectively, indicates that the temperate shelf-seas cover slightly less than a half of the area and support a commensurate fraction of the primary production in the world's shelf-seas while receiving about one-quarter of the global riverine discharge (Fig. 1). On the other hand, the tropical shelf-seas account for about one-third of the area of all shelf-seas but they are responsible for 40% of the primary production and receive two-thirds of the global riverine discharge. Thus, temperate shelf-seas constitute a significant, but by no means overwhelming, fraction of all the shelf-seas. Furthermore, tropical shelf-seas, while constituting a substantial fraction of the shelf-seas, can also be affected disproportionately by land runoff, which is highly sensitive to human activities and global climate changes. In this regard, in comparison to temperate shelf-seas, tropical shelf-seas seem understudied, especially in view of the fact that they may well respond differently to anthropogenic and natural environmental changes. Data from the tropical sub-regions would certainly be of necessity in constructing an accurate global picture on the present and future behaviors of the shelf-seas.

The Island of Taiwan straddles across the Tropic of Cancer. Two large shelf seas: The temperate East China Sea and the tropical Northern South China Sea (NoSoCS) (Fig. 2), are within easy reach from the Island. Taiwanese oceanographers have had a long history in studying the oceanography of the shelf-seas. However, their effort, especially in the past few decades, has been devoted almost exclusively to the East China Sea through a series of multidisciplinary integrated projects such as the Kuroshio Edge Exchange Processes (KEEP) study and the Long-term Observation and Research of the East China Sea (LORECS) (Wong and Wang, 1992; Chao et al., 1995; Wong et al., 2000; Liu et al., 2003; Gong et al., 2011). In the South China Sea (SCS), although there had been some concerted efforts to study the open northern SCS (Wong et al., 2007a; Ramp and Tang, 2011), studies involving the NoSoCS have been much more limited and fragmented (Chen, 2005; Chen and Chen, 2006). Across the Taiwan Strait, past efforts of the Chinese oceanographers on the NoSoCS have focused on its northern part, especially around Dongshan and the Taiwan Bank, where upwelling occurs (Hong et al., 1991; Wong et al., 2011). There has been an ongoing effort among oceanographers from China and Hong Kong to study the Pearl River estuary, but the study area does not extend much beyond the inner shelf in the vicinity of the River's mouth (Harrison, 2004; Dai et al., 2008a, 2008b; Guo et al., 2008; Xu et al., 2008, 2009; Han et al., 2012). A comprehensive synoptic study of the entire NoSoCS has not yet been reported in the literature.

The present study is an effort to fill this gap and provide an overall description of the oceanography of the NoSoCS as a case study of the under-studied tropical shelf-seas. It represents primarily the work of Taiwanese oceanographers, with significant contributions from investigators from Hong Kong.

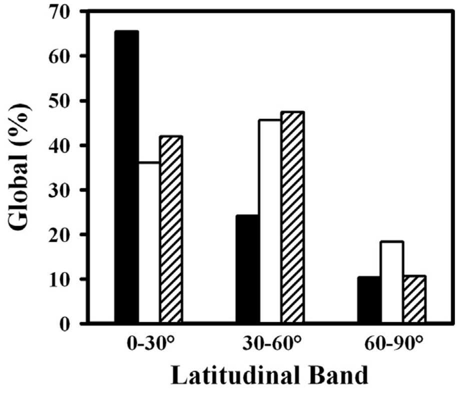

Fig. 1. The percentage of global total in riverine discharge (solid bar), shelf surface area (open bar) and shelf primary production (slashed bar) at latitudes 0–30°, 30–60° and 60–90°, based on data from Walsh (1988).

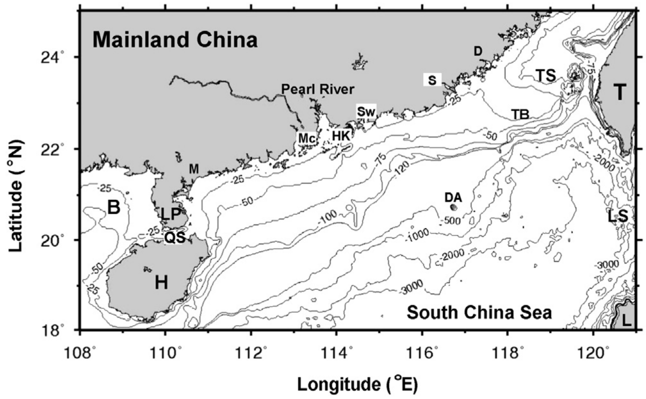

Fig. 2. The *No*rthern *So*uth *C*hina *S*ea (NoSoCS) and its adjacent Waters. B—Beibu Gulf; DA—Dongsha Atoll; H—Hainan Island; HK—Hong Kong; L—Luzon Island; LP—Leizhou Peninsula; LS—Luzon Strait; QS—Qongzhou Strait; T—Taiwan; TB—Taiwan Bank; TS—Taiwan Strait; D—Dongshan; M—Maoming; Mc—Macau; S—Shantou; Sw—Shanwei.

Table 1
Sampling cruises in the Northern South China Sea Shelf-sea (NoSoCS) Study.

Cruise	Date	Sampling Locations[a]
OR3-1379	Jun 10–15, 2009	Test cruise[b]
OR1-929	June 2–15, 2010	Transects T1-T4
OR1-953	Dec. 29, 2010–Jan. 10, 2011	Transects T1 and T4
OR1-988	Dec. 19–29, 2011	Transect T3
OR1-1010	Aug. 28–Sep. 4, 2012	Transect T3
OR1-1015	Oct. 12–21, 2012	Around Dongsha Atoll

[a] T1, T2, T3, T4—transects perpendicular to coastline from Shantou, Shanwei, Macau and Maoming to the open South China Sea (Fig. 2).

[b] One transect from Hong Kong through the Dongsha Atoll to the open South China Sea (Fig. 2).

The Taiwanese effort, the NoSoCS Study, was initiated in 2009 with the financial support from the Ministry of Science and Technology (MOST, formerly known as the National Science Council). The initial design of the sampling program was to cover the entire NoSoCS in four approximately equally spaced cross-shelf transects that extend approximately perpendicular to the shoreline from around Shantau, Shanwei, Macau and Maoming to the open northern SCS (Fig. 2). After 2011, the sampling program was reduced to one cross-shelf transect off Macau in two different seasons in each year. While the project sponsored by the MOST was ongoing, process-studies were launched with the financial support of the Academia Sinica to study the response of the sub-regions in the NoSoCS to atmospheric forcing and to the effect of Ocean acidification. The field data reported here came primarily from all these efforts in five cruises conducted in the summer of 2009, 2010 and 2012, the winter of 2011 and 2012 and the fall of 2012 (Table 1). The NoSoCS Study is still ongoing. In coming years, sampling during the other seasons will be conducted.

Table 2
Some characteristics of the Northern South China Sea Shelf-sea (NoSoCS).

Average width (km)	200	
Length (km)	750	
Area (10^4 km^2)		
Total	16.11	
Inner shelf (< 40 m)	6.50	
Middle shelf (40-90 m)	6.78	
Outer shelf (90-120 m)	2.83	
Volume (10^3 km^3)		
Total	8.08	
Inner shelf (< 40 m)	1.12	
Middle shelf (40–90 m)	4.22	
Outer shelf (90—120 m)	2.73	
Average depth (m)		
Total	50	
Inner shelf (< 40 m)	17	
Middle shelf (40–90 m)	62	
Outer shelf (90–120 m)	96	
Annual precipitation (mm y^{-1})	2398	(1)
June to September (mm)	1592	
October to April (mm)	501	
Annual evaporation (mm y^{-1})	1227	(1)
June to September (mm)	524	
October to April (mm)	593	
Excess precipitation (mm y^{-1})	1171	
June to September (mm)	1068	
October to April (mm)	-91	
Pearl River inflow (km^3 y^{-1})	330	(2)
Ground water inflow (km^3 y^{-1})		(3)
Net ground water	4–7	
Submarine ground water[a]	80–135	
Mixed layer depth (m)		(4)
Summer	40	
Winter	70	

(1) Hong Kong Observatory Climatological Information Services, 2014; (2) Guo et al., 2008; (3) Liu et al., 2012; (4) Wong et al., 2015.

[a] Mostly recirculated seawater.

2. The *N*orthern *S*outh *C*hina Sea *S*helf-Sea (NoSoCS): environmental setting

The NoSoCS (Fig. 2) is a fairly well defined tropical shelf-sea that forms the northwestern boundary of the SCS. It is orientated approximately in a northeast-to-southwest direction, as it extends from a ridge system that marks the southern end of the Taiwan Strait at about 23°N and 119°E to the northeastern coasts of the Leizhou Peninsula and the Hainan Island at about 20°N and 111°E; total length is about 750 km. It stretches from the coast of southern China to the shelf break at the 120 m isobath, with an average width of about 200 km. It thus covers an area of 1.6×10^4 km^2 with an average depth of 50 m. At its northeastern boundary, free exchange with the Taiwan Strait is restricted by the ridge that extends seaward from Dongshan. The offshore portion of this ridge forms the Taiwan Bank where the Water depth can be reduced to less than 20 m. The maximum Water depth along the ridge occurs in a channel between Dongshan and the Taiwan Bank, and it does not exceed 40 m. As a result of this ridge system, the shelf broadens from the southwest towards the northeast. Thus, the 50 m isobath is only about 50 km from the coast off Maoming at the southern end but it is 80 km from the coast off Shantou at the northern end of the NoSoCS. At its southwestern boundary, the NoSoCS is connected to the Beibu Gulf through the narrow Qongzhou Strait which is situated between the Leizhou Peninsula and the Hainan Island. At its seaward boundary, there is free exchange between the NoSoCS and the open northern SCS. A summary of some of the physical characteristics of the NoSoCS is presented in Table 2.

As part of the SCS, which is situated between the western Pacific warm pool and the Tibetan Plateau, the NoSoCS is subject to the persistent influence of the monsoonal winds. The stronger northeast monsoon lasts between November and April while the weaker southwest monsoon occurs between June and September, and they are separated by the short inter-monsoonal periods in May and September. These monsoonal winds are an important determining factor of the behaviors of the NoSoCS. Thus, a northeastward flowing coastal current is found in the summer while a southwestward flowing coastal current occurs in the winter in response to the changes in the wind direction (Gan et al., 2006, 2009, 2013). About two-thirds of the precipitation occurs between June and September when the southwest monsoon brings warm humid air to the area. In contrast, evaporation actually exceeds precipitation in October through April when the northeast monsoon brings cold dry air to the region (Table 2); for the entire year, precipitation exceeds evaporation.

The Pearl River (Zhujiang), which is the 13th largest river in the world, is the primary source of freshwater that empties into the NoSoCS. It drains into the NoSoCS at about its mid-point at 114°E with an average annual Water discharge of 330 km^3/yr (Guo et al., 2008). The minimum flow of the Pearl River occurs during the winter and the maximum flow rate is reached in the summer in around July, in step with the intra-annual variations in the rate of precipitation in the region (Wong et al., 2007a). The drainage basin of the Pearl River is among the most rapidly growing economic regions of the world. As a result, there is a significant anthropogenic influence on the river, and this is reflected in the high concentrations of organic substances, nutrients and metals and low concentrations of oxygen in Pearl River Water (Zhang, 1995; Chen et al., 2004; Yin et al., 2004; Yin and Harrison, 2008; Dai et al., 2014). As such, the NoSoCS, especially on its inner shelf, will have its biogeochemistry heavily influenced by the inflow of this urbanized River (Dai et al., 2008a). Aside from riverine input, the anthropogenic material from the Pearl River basin can also find its way to the NoSoCS as submarine groundwater discharge (Liu et al., 2012) and through eolian transport (Lin et al., 2007, 2009). However, while the riverine input of many elements through the Pearl River is reasonably well known (Zhang, 1995, 1996), the inputs from these two other sources are still poorly characterized and quantified.

At its seaward boundary, the NoSoCS is bounded by a current that flows southwestward along the continental margin as part of the circulation in the SCS basin (Gan et al., 2006). At the frontal zone, mass exchange between the NoSoCS and the current occurs through frontal and meso-scale dynamic processes. Furthermore, some of the strongest internal waves of the world are found at the outer shelf and the adjacent upper slope of the NoSoCS (Hsu et al., 2000). These waves are generated at the Luzon Strait and they propagate westward along the bottom of the mixed layer as packets of solitons. As the mixed-layer depth in the northern SCS is shallower than the shelf break depth of the NoSoCS, these internal waves eventually reach the shallower Waters in the NoSoCS where they undergo transformation and destruction. Mass exchange will then occur between the mixed layer and the sub-surface Water. While these internal waves may reach the entire outer shelf of the NoSoCS, the most extensive activities are found in the Dongsha Plateau north of the Dongsha Atoll, where the amplitude of individual solitons may reach depths in excess of 150 m (Farmer et al., 2011), and in the area northeast of the Hainan Island (Li et al., 2008; Guo et al., 2012).

Several types of upwelling have been reported to occur in the NoSoCS. The classical wind-induced upwelling occurs in the summer along the northeastern coasts of the Hainan Island during the southwest monsoon (Jing et al., 2009). The upwelling off the shore of Dongshan–Shantou at the northeastern corner of NoSoCS in the summer is driven by the combined effect of wind and topography (Gan et al., 2009, 2010; Gu et al., 2012). The intrusion of the Kuroshio into the northern SCS from the Philippine Sea impinges on the outer shelf of the NoSoCS and leads to the topographically induced upwelling at the Taiwan Bank which may occur at varying strengths year-round (Hong et al., 1991).

3. Highlights

3.1. Regional characteristics and physical dynamics

The mixed-layer depth in the Oceans tends to become shallower with decreasing latitude (Montégut et al., 2004). Wong et al. (2015) reported that the mixed-layer depth in the NoSoCS, about 40 m in the summer and 70 m in the winter, is indeed relatively shallow, and it is shallower than the shelf break depth, which is about 120 m. The mixed-layer depth in the adjacent open northern SCS at the Southeast Asian Time-series Station (SEATS) has been reported to be about 20 m in the summer and 70 m in the winter (Wong et al., 2007a, 2007b). As a result, a layer of colder upper thermocline-upper nutricline Water with moderately high concentrations of the nutrients can extend freely onto the NoSoCS from the open SCS below the mixed layer and covers a significant fraction of its seabed throughout the year. This is a distinguishing characteristic of the NoSoCS. In other shelf-seas, such as the East China Sea and the South Atlantic Bight, where the mixed-layer depth in the adjoining deep Water exceeds the shelf break depth, the upper nutricline Water does not have free access to the shelf-sea. Upwelling over the shelf break is necessary for supplying the nutrients in the sub-surface Waters off the shelf to the shelf-seas (Lee et al., 1991; Wong et al., 1991, 2004). In the NoSoCS, this is not required and was not observed. Instead, vertical mixing on the shelf, which may be caused by a variety of processes operating in different temporal and spatial scales, is a major control on the availability of nutrients to the mixed layer. These processes include convective overturn over the entire NoSoCS in the winter, sub-regional formation of bottom Water at the outer inner shelf and the inner middle shelf in the winter, upwelling off Dongshan–Shantou and northeast of Hainan Island in the summer and off the Taiwan Bank year-round, and, the action of internal waves along the outer shelf (Pan et al., 2015). The formation of bottom Water in the winter provides a rare direct observation of the occurrence of the "continental shelf pump" that has been hypothesized for some time (Tsunogai et al., 1999). In the sub-regional scale, by combining observational with numerical modeling studies, Gan et al. (2015) found that the dynamic control resulted from the widened shelf topography plays a critical role in the cross-isobath transport over the continental shelf in the NoSoCS in the summer that sustains the coastal upwelling off Dongshan-Shantou. These dynamics allow the upwelling to continue even during episodes of wind-stress conditions that do not favor upwelling.

Based on remote-sensing data, Pan et al. (2015) reported a unique seasonal pattern in the variations of the concentration of chlorophyll-a and the associated primary production in the NoSoCS that is different from those generally found in the polar, temperate or tropical Waters (Heinrich, 1962): two distinct maxima, one in December–January and one in July during the heights of the monsoonal seasons. The winter maximum, which is also found in the adjoining open SCS (Tseng et al., 2005), is probably similarly linked to the increase in biological activity as a result of the increase in the supply of nutrients from the sub-surface by the enhanced vertical mixing caused by surface cooling and the strong northeast monsoon. The summer maximum may reflect the influence of the nutrient supply from terrestrial sources, when the runoff from the Pearl River reaches its maximum, together with the contributions from coastal upwelling and the stronger internal waves. In the Pearl River estuary, Zu and Gan (2015) found that the sub-tidal circulation is governed by an advective gravitational circulation that is modulated by the intrusion from the shelf in the seaward part of the lower estuary. Upwelling circulation enhances the exchange of Water between the Pearl River estuary and the NoSoCS.

3.2. Biological processes

The temporal and spatial variations in phytoplankton biomasses in the NoSoCS deduced from remotely sensed data (Pan et al., 2012, 2013, 2015) were largely confirmed by field observations (Ho et al., 2015). Thus, in the offshore Waters at and beyond the outer shelf, elevated phytoplankton abundance and pigment concentration are found in the winter. On the other hand, in inshore Waters, in addition to the winter maxima, higher phytoplankton abundance and pigment concentrations are also found in the summer. The distributions of the individual pigments indicate that the phytoplankton community structures in the NoSoCS and its adjacent Waters are highly spatially and temporally variable (Ho et al., 2015), probably as a reflection of the dynamic hydrographic and nutrient conditions in the study area (Wong et al., 2015). Divinyl chlorophyll-a and Zeaxanthin, which are indicative of the presence of the smaller phytoplankta *Prochlorococcus* and *Synechococcus,* are more abundant in the nutrient-poor offshore surface Waters than in the more nutrient-replete coastal surface Waters, and, more abundant in summer than in winter. In contrast, Fucoxanthin, which is indicative of the presence of the larger phytoplankton *diatoms,* is more abundant in the more nutrient-rich coastal Waters, and this is especially evident in the winter. Close association between soluble reactive phosphate and chlorophyll-a concentration was observed, indicating that nutrient supply is the major controlling factor on the temporal and spatial variations of phytoplankton distribution. Sub-regionally, Lu and Gan (2015) reported that physical-biological forcing controls the seasonally variable distribution of phytoplankton biomass along the longitudinal axis in the Pearl River estuary. During the dry winter season, the maximum phytoplankton biomass occurs in the mid-estuary. The high turbidity farther upstream and the strong vertical mixing further downstream restrict the growth of phytoplankton in those sub-regions of the estuary. On the other hand, during the wet season in the summer, the maximum phytoplankton biomass is found in the lower estuary where the phytoplankton growth rate can exceed the Water turnover rate.

At a higher trophic level, Chen et al. (2015) reported that, in the open northern SCS, the bottom-up effect is evident in the variations in the mesozooplankton biomass as they follow those in the phytoplankton biomass closely such that, as the latter increases, the former also increases and reaches a maximum in the late spring. Among the size fractions, the larger ($>1000\ \mu m$) mesozooplanktons contribute the bulk of the biomass and grazing impact, and thus may play an important role in the downward transport of carbon. The control on phytoplankton biomass by mesozooplankton grazing is also size-dependent. It is more substantial for the larger ($>2\ \mu m$) phytoplankton.

Through gene sequencing, Xia et al. (2015) found that the community structure of prokaryotes (bacteria and archaea) in the northern SCS varied across space and over time, and this variation was strongly correlated with nitrate concentration. Major bacterial and archaeal lineages showed different niche preferences. For example, cyanobacteria subcluster 5.2 *Synechococcus* dominated in estuarine Water, while subcluster 5.1 clade II *Synechococcus* dominated in coastal and shelf Waters. Euryarchaeota was the dominant archaea in the oceanic surface Water, whereas Crenarchaeota was more abundant in estuarine and coastal Waters.

3.3. Biogeochemical processes

Guo and Wong (2015) reported that the distributions of the different parameters in the carbonate system of the NoSoCS are controlled by different combinations of processes. While the distribution of titration alkalinity can be accounted for almost exclusively by mixing between the surface and subsurface Water, the distribution of dissolved inorganic carbon is further affected by the exchange of CO_2 with the atmosphere and by biological uptake. The distributions of pCO_2 and in situ pH are also influenced by temperature change. At an evasion rate of 0.6 $mmol\ C\ m^{-2}\ d^{-1}$, the NoSoCS is a net source of CO_2 to the atmosphere. The net community production rate averages 13.2 $mmol\ C\ m^{-2}\ d^{-1}$. It is much elevated in the coastal upwelling areas, where it may reach 30.1 $mmol\ C\ m^{-2}\ d^{-1}$. Although the Water in the NoSoCS is super-saturated with respect to aragonite at all depths, the degree of saturation, 3.3 to 3.7, is at a level that has been considered to be only barely adequate to marginal for the growth of the shallow-Water tropical corals (Kleypas et al., 1999; Guinotte et al., 2003).

Pan and Wong (2015) described an algorithm for deducing the distribution of DOC from remotely sensed data and they used it for developing the climatological distribution of DOC in the surface Waters in the NoSoCS. The patterns in the spatial variations are in good agreement with those observed in other coastal Waters. The seasonal variations in the concentration of DOC, with a maximum in the summer and a minimum in the winter, are out of phase with that of phytoplankton (Pan et al., 2015). The low concentrations in the winter likely result from the enhanced vertical mixing, which brings the relatively DOC-poor subsurface Water to the surface mixed layer. On the other hand, the higher terrestrial inputs may have led to the higher concentrations of DOC in the summer. The production of DOC in biological activities does not seem to be the primary controlling factors on this seasonal pattern.

Wu et al. (2015) reported that, in the surface Waters, the distribution of the photochemically produced H_2O_2 in the NoSoCS can be accounted for by the light history, the pre-existing concentration of H_2O_2 and the concentration and photochemical efficiency of the chromophore, namely, dissolved organic matter, in the Water. As a result, the highest concentrations of H_2O_2 are found in day time in the inner shelf away from the upwelling zone while the lowest concentrations occur in the night time in the upwelling zone. In terms of depth variations, although the typical distribution of a quasi-exponential decrease in concentration with depth can be found in a majority of the profiles, it is rarely found in areas where internal waves are known to be active. Instead, significant concentrations of H_2O_2 can be found down to about 100 m, well beyond the depths where solar irradiance is plentiful. The origin of this heretofore unreported elevation in the concentration of H_2O_2 in sub-surface Waters beyond the euphotic zone is uncertain. Dark biological production is a possibility, and the high bacterial activity found in these Waters (Lai et al., 2014) is consistent with this possibility.

For the particle-reactive radioactive nuclides ^{210}Pb and ^{210}Po, their distributions in the northern SCS are greatly influenced by particle scavenging (Wei et al., 2015). Thus, the scavenging residence time of ^{210}Pb decreases from months to weeks from the particle-poor open SCS to the more particle-rich NoSoCS. The affinities of ^{210}Pb and ^{210}Po to particles can be different as about 25% of ^{210}Pb but only $<10\%$ of ^{210}Po are found in the particulate phase and the scavenging residence times of ^{210}Pb are shorter and are invariably in terms of months.

Acknowledgments

This work was supported in part by the Ministry of Science and Technology of Taiwan through Grant NSC 101-2611-M-001-003-MY3 (to Wong) and by the Academia Sinica through a thematic project grant titled “Ocean Acidification: Comparative biogeochemistry in shallow-Water tropical coral reef ecosystems in a naturally acidic marine environment “ (to Wong). This manuscript was completed while Wong was a visiting professor at the Hong Kong University of Science and Technology and at the University of Malaya.

References

Borges, A.V., 2005. Do we have enough pieces of the jigsaw to integrate CO_2 fluxes in the coastal Ocean? Estuaries 28, 3–27.

Borges, A.A., Delille, B., Frankignoulle, M., 2005. Budgeting sinks and sources of CO_2 in the coastal Ocean: Diversity of ecosystem counts. Geophys. Res. Lett. 32 (L14601), 1–4. http://dx.doi.org/10.1029/2005GL023053.

Brooks, J.M., Reid, D.F., Bernard, B.B., 1981. Methane in the upper Water column of the northwestern Gulf of Mexico. J. Geophys. Res. 86, 11029–11040.

Buddemeier, R.W., Smith, S.V., Swaney, D.P., Crossland, C.J., 2002. The role of the coastal Ocean in the disturbed and undisturbed nutrient and carbon cycles. LOICZ/UNEP, Texel, The Netherlands p. 83, LOICZ Reports & Studies No. 24.

Cai, W.-J., Dai, M., 2004. Comment on “Enhanced open Ocean storage of CO_2 from shelf Sea pumping”. Science 306, 1477.

Cai, W.-J., Dai, M., Wang, Y., 2006. Air-sea exchange of carbon dioxide in Ocean margins: a province-based synthesis. Geophys. Res. Lett. 33 (L12603), 1–4. http://dx.doi.org/10.1029/2006GL026219.

Cai, W.-J., Hu, X., Huang, W.-J., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W.-C., Zhai, W., Hollibaugh, J.T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., Gong, G.-C., 2011. Acidification of subsurface coastal Waters enhanced by eutrophication. Nat. Geosci. 4, 766–770. http://dx.doi.org/10.1038/NGEO1297.

Chao, S.-y., Chung, Y.-C., Chen, C. (guest editors) 1995. KEEP-MASS special issue. Terrestrial, Atmospheric and Oceanic Sciences 6, 1-165.

Chen, Y.-l.L., 2005. Spatial and seasonal variations of nitrate-based new production and primary production in the South China Sea. Deep-Sea Res. I 52, 319–340.

Chen, Y.-l.L., Chen, H.-Y., 2006. Seasonal dynamics of primary and new production in the northern South China Sea: The significance of River discharge and nutrient advection. Deep-Sea Res. I 53, 971–986.

Chen, Z., Li, Y., Pan, J., 2004. Distribution of colored dissolved organic matter and dissolved organic carbon in the Pearl River Estuary, China. Cont. Shelf Res. 24, 1845–1856.

Chen, M., Liu, H., Song, S., Sun, J., 2015. Size-fractionated mesozooplankton biomass and grazing impacts on phytoplankton in northern South China Sea. Deep-Sea Res. II. 117, 108–118.

Dai, M., Wang, L., Guo, X., Zhai, W., Li, Q., He, B., Kao, S.-J., 2008a. Nitrification and inorganic nitrogen distribution in a large perturbed River/estuarine system: the Pearl River Estuary, China. Biogeosciences 5, 1227–1244.

Dai, M., Zhai, W., Cai, W.-J., Callahan, J., Huang, B., Shang, S., Huang, T., Li, X., Lu, Z., Chen, W., Chen, Z., 2008b. Effects of an estuarine plume-associated bloom on the carbonate system in the lower reaches of the Pearl River estuary and the coastal zone of the northern South China Sea. Cont. Shelf Res. 28, 1416–1423.

Dai, M., Gan, J., Han, A., Kung, H.S., Yin, Z., 2014. Physical dynamics and biogeochemistry of the Pearl River plume. In: Bianchi, T., Allison, M., Cai, W.-J. (Eds.), Biogeochemical Dynamics at Major River-Coastal Interfaces Linkages with Global Change. Cambridge University Press, New York, pp. 321–352.

Farmer, D.W., Alford, M.H., Lien, R.-C., Yang, Y.J., Chang, M.-H., Li, W., 2011. From Luzon Strait to Dongsha Plateau: Stages in the life of an internal wave. Oceanography 24, 64–77.

Gan, J., Li, H., Curchitser, E.N., Haidvogel, D.B., 2006. Modeling South China Sea circulation: response to seasonal forcing regimes. J. Geophys. Res. 111, C06034. http://dx.doi.org/10.1029/2005JC003298.

Gan, J., Cheung, A., Guo, X.G., Li, L., 2009. Intensified upwelling over a widened shelf in the northeastern South China Sea. J. Geophys. Res. 114, C09019. http://dx.doi.org/10.1029/2007JC004660.

Gan, J., Lu, Z., Dai, M., Cheung, A.Y.Y., Liu, H., Harrison, P., 2010. Biological response to intensified upwelling and to a River plume in the northeastern South China Sea: a modeling study. J. Geophys. Res. 115, C09001. http://dx.doi.org/10.1029/2009JC005569.

Gan, J., Ho, H.S., Liang, L., 2013. Dynamics of intensified downwelling circulation over a widened shelf in the northeastern South China Sea. J. Phys. Oceanogr. 43, 80–94.

Gan, J., Wang, J., Liang, L., Li, L., Guo, X., 2015. A modeling study of the formation, maintenance, and relaxation of upwelling circulation on the Northeastern South China Sea Shelf. Deep-Sea Res. II. 117, 41–52.

Gong, G.C., Liu, K.-K., Chiang, K.P., Hsiung, T.M., Chang, J., Chen, C.-C., Hung, C.C., Chou, W.-C., Chung, C.-C., Chen, H.-Y., Shiah, F.-K., Tsai, A.-Y., Hsieh, Ch.-H., Shiao, J.-C., Tseng, C.-M., Hsu, S.-C., Lee, H.J., Lee, M.-A., Lin, I-I, Tsai, F., 2011. Yangtze River floods enhance coastal ocean phytoplankton biomass and potential fish production. Geophys. Res. Lett. 38, L13603. http://dx.doi.org/10.1029/2011GL047519.

Gu, Y., Pan, J., Lin, H., 2012. Remote sensing observation and numerical modeling of an upwelling jet in Guangdong coastal Water. J. Geophys. Res.-Ocean 117, C08019. http://dx.doi.org/10.1029/2012JC007922.

Guinotte, J.M., Buddemeier, R.W., Kleypas, J.A., 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22 (4), 551–558.

Guo, X., Wong, G.T.F., 2015. Carbonate chemistry in the northern South China Sea shelf-sea in June 2010. Deep-Sea Res. II. 117, 119–130.

Guo, X., Cai, W.-J., Zhai, W., Dai, M., Wang, Y., Chen, B., 2008. Seasonal variations in the inorganic carbon system in the Pearl River (Zhujiang) estuary. Cont. Shelf Res. 28, 1424–1434.

Guo, C., Vlasenko, V., Alpers, W., Stashchuk, N., Chen, X., 2012. Evidence of short internal waves trailing strong internal solitary waves in the northern South China Sea from synthetic aperture radar observations. Remote Sens. Environ. 124, 542–550.

Han, A., Dai, M., Kao, S.-J., Gan, J., Li, Q., Wang, L., Zhai, W., Wang, L., 2012. Nutrient dynamics and biological consumption in a large continental shelf system under the influence of both a River plume and coastal upwelling. Limnol. Oceanogr. 57, 486–502.

Harrison, P.J. (Ed.), 2004. Pearl River Estuary Study. Continental Shelf Research 24, pp. 1737–1987.

Heinrich, A.K., 1962. The life histories of plankton animals and seasonal cycles of plankton communities in the oceans. J. Cons. Int. pour Explor. Mer. 27, 15–24.

Ho, T.Y., Pan, X., Yang, H.-H., Wong, G.T.F., Shiah, F.-K., 2015. Controls on temporal and spatial variations of phytoplankton pigment distribution in the northern South China Sea: spatial and seasonal variability. Deep-Sea Res. II. 117, 65–85.

Hong, H., Qiu, S., Ruan, W., Hong, G. (Eds.), 1991. Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study. Science Publishing, Beijing, p. 703.

Hong Kong Observatory Climatological Information Services, 2014. Monthly meteorological normal for Hong Kong between 1981 and 2010. ⟨http://www.hko.gov.hk/cis/normal/1981_2010/normals_e.htm⟩.

Hsu, M.-K., Liu, A.K., Liu, C., 2000. A study of internal waves in the China Seas and Yellow Sea using SAR. Cont. Shelf Res. 20, 389–410.

IMBER, 2005. Integrated Marine Biogeochemistry and Ecosystem Research Science Plan and Implementation Strategy. IGBP Secretariat, Stockholm, Sweden p. 76, IGBP Report 52.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. In: Pachauri, R.K., Reisinger, A. (Eds.), IPCC, Geneva, Switzerland, p. 104.

JGOFS, 1992. Joint Global Ocean Flux Study Implementation Plan. JGOFS Report no. 9. IGBP Secretariat, Stockholm, Sweden, IGBP Report 23.

Jing, Z.-y., Qi, Y.-q., Hua, Z.-l., Zhang, H., 2009. Numerical study on the summer upwelling system in the northern continental shelf of the South China Sea. Cont. Shelf Res. 29, 467–478.

Kleypas, J.A., McManus, J.W., Menez, L.A.B., 1999. Environmental limits to coral reef development: Where do we draw the line? Am. Zool. 39 (1), 146–159.

Lai, C.-C., Fu, Y.-W., Liu, H.-B., Kuo, H.-Y., Wang, K.-W., Lin, C.-H., Tai, J.-H., Wong, G.T. F., Lee, K.Y., Chen, T.-Y., Yamamoto, Y., Chow, M.-F., Kobayashi, Y., Ko, C.-Y., Shiah, F.-K., 2014. Distinct bacterial-production-DOC-primary-production relationships and implications for biogenic C cycling in the South China Sea shelf. Biogeosciences 11, 147–156.

Lee, T., Yoder, J., Atkinson, L., 1991. Gulf Stream frontal eddy influence on productivity of the southeast US continental shelf. J. Geophys. Res. 96, 22191–22205.

Li, X., Zhao, Z., Pichel, W.G., 2008. Internal solitary waves in the northwestern South China Sea inferred from satellite images. Geophys.Res. Lett. 35, L13605. http://dx.doi.org/10.1029/2008GL034272.

Lin, I.-I., Chen, J.-P., Wong, G.T.F., Huang, C.-W., Lien, C.-C., 2007. Aerosol input to the South China Sea: results from the MODerate resolution imaging spectroradiometer, the quick scatterometer, and the measurements of pollution in the troposphere sensor. Deep-Sea Res. II 54, 1589–1601. http://dx.doi.org/10.1016/j.dsr2.2007.05.013.

Lin, I.-I., Wong, G.T.F., Huang., C.-W., Lien, C.-C., 2009. Aerosol impact on the South China Sea biogeochemistry—an early assessment from remote sensing. Geophys. Res. Lett. 36 (L17605), 1–5, doi:10.1029GL037484.

Liu, K.-K., Atkinson, L., Chen, C.T.A., Gao, S., Ha, J., Macdonald, R.W., McManus, T., Quiñones, R., 2000. Exploring continental margin carbon fluxes on a global scale. EOS 81 (52), 641–642.

Liu, K.-K., Peng, T.-H., Shaw, P.-T., 2003. Circulation and biogeochemical processes in the East China Sea and the vicinity of Taiwan. Deep-Sea Res. II 50, 1055–1333.

Liu, K.-K., Atkinson, L., Quiñones, R., Talaue-McManus, L. (Eds.), 2010. Carbon and Nutrient Fluxes in Continental Margins. Springer-Verlag, Berlin, p. 741.

Liu, Q., Dai, M., Chen, W., Huh, C.-A., Wang, G., Li, Q., Charette, M.A., 2012. How significant is submarine groundwater discharge and its associated dissolved inorganic carbon in a River-dominated shelf system? Biogeosciences 9, 1777–1795.

Lu, Z., Gan, J., 2015. Controls of seasonal variability of phytoplankton blooms in the Pearl River Estuary. Deep-Sea Res. II. 117, 86–96.

Mckenzie, F.T., 2010. Preface. In: Liu, K.-K., Atkinson, L., Quiñones, R., Talaue-McManus, L. (Eds.), Carbon and Nutrient Fluxes in Continental Margins. Springer-Verlag, Berlin, vii–x.

Montégut, C., de, B., Madec, G., Fischer, A.S., Lazar, A., Iudicone, D., 2004. Mixed laer depth over the global Ocean: an examination of profile data and a profile-based climatology. J. Geophys. Res. 109 (C12003), 20. http://dx.doi.org/10.1029/2004JC002378.

Moore, C.A., Farmer, C.T., Zika, R.G., 1993. Influence of the Orinoco River on hydrogen peroxide distribution and production in the Eastern Caribbean. J. Geophys. Res. 98 (C2), 2289–2298.

Nozaki, Y., Thomson, J., Turekian, K.K., 1976. The distribution of 210Pb and 210Po in the surface Waters of the Pacific Ocean. Earth Planet. Sci. Lett. 22, 304–312.

Pan, X., Wong, G.T.F., 2015. An improved algorithm for remotely sensing marine dissolved organic carbon: climatology in the northern South China Sea Shelf-sea and adjacent Waters. Deep-Sea Res. II. 117, 131–142.

Pan, X., Wong, G.T.F., Shiah, F.-K., Ho, T.-Y., 2012. Enhancement of biological productivity by internal waves: observations in the summertime in the northern South China Sea. J. Oceanogr. 68, 427–437.

Pan, X., Wong, G.T.F., Ho, T.-Y., Shiah, F.-K., Liu, H., 2013. Remote sensing of picophytoplankton distribution in the northern South China Sea. Remote Sens. Environ. 128, 162–175.

Pan, X., Wong, G.T.F., Tai, J.H., Ho, T.-Y., 2015. Climatology of physical and biological characteristics of the northern South China Sea Shelf-sea (NoSoCS) and adjacent Waters: observations from satellite remote sensing. Deep-Sea Res. II. 117, 10–22.

Postma, H., Zijlstra, J.J. (Eds.), 1988. Continental Shelves. Elsevier, Amsterdam, p. 421.

Ramp, S.R., Tang, T.Y., 2011. A history of Taiwan/US oceanographic research in the South China Sea. Oceanography 24, 16–23.

Ryther, J.H., 1969. Photosynthesis and fish production in the sea. Science 166, 72–76.

SOLAS, 2004. The Surface Ocean-Lower Atmosphere Study. Science Plan and Implementation Strategy. IGBP Secretariat, Stockholm, Sweden p. 88, IGBP Report 50.

Thomas, H., Bozec, Y., Elkalay, K., de Baar, H.J.W., 2004. Enhanced open ocean storage of CO_2 from shelf sea pumping. Science 304, 1005–1008.

Tseng, C.-M., Wong, G.T.F., Lin, I.-I., Wu, C.-R., Liu, K.-K., 2005. A unique seasonal pattern in phytoplankton biomass in low-latitude Waters in the South China Sea. Geophys. Res. Lett. 32, L08608. http://dx.doi.org/10.1029/2004GL022111.

Tsunogai, S., Watanabe, S., Sato, T., 1999. Is there a “continental shelf pump” for the absorption of atmospheric CO_2? Tellus 51B, 701–712.

USGOFS, 1987. Ocean Margins in GOFS. U.S. GOFS Planning Report No. 6. U.S. GOFS Planning and Coordination Office. Woods Hole, MA. p. 244.

Walsh, J.J., 1988. On the Nature of Continental Shelves. Academic Press, San Diego p. 520.

Wei, C.-L., Wong, G.T.F., Sun, S.-J., Gong, G.-C., 2001. Extractable manganese in the southeastern East China Sea and the Okinawa Trough. Oceanol. Acta 24, S99–S111.

Wei, C.-L., Chen, P.-R., Lin, S.-Y., Sheu, D.D., Wen, L.-S., Chou, W.-C., 2015. Distributions of ^{210}Pb and ^{210}Po in surface Waters surrounding Taiwan: A synoptic observation. Deep-Sea Research II. 117, 155–166.

Wong, G.T.F., 1995. Dissolved iodine across the Gulf Stream front and in the South Atlantic Bight. Deep Sea Res. 42, 2005–2023.

Wong, G.T.F., Wang, D.-P. (guest editors), 1992. Special issue on KEEP. Terrestrial, Atmospheric and Oceanic Sciences 3, pp. 225-447.

Wong, G.T.F., Pai, S.-C., Liu, K.-K., Liu, C.-T., Chen, G.-T.A., 1991. Variability of the chemical hydrography at the frontal region between the East China Sea and the Kuroshio north-east of Taiwan. Estuar. Coas. Shelf Sci. 33, 105–120.

Wong, G.T.F., Li, Y.-H., Chao, S.-Y., Chung, Y.-C. (guest editors) 2000. Kuroshio Edge Exchange Processes (KEEP)—Interactions between the East China Sea and the Kuroshio. Continental Shelf Research 20, pp. 331–635.

Wong, G.T.F., Hung, C.-C., Gong, G.-C., 2004. Dissolved iodine species in the East China Sea—a complementary tracer for upwelling Water on the shelf. Cont. Shelf Res. 24, 1465–1484.

Wong, G.T.F., Ku, T.-L., Mulholland, M., Tseng, C.-M., Wang, D.-P., 2007a. The SouthEast Asian Time-series Study (SEATS) and the biogeochemistry of the South China Sea—an overview. Deep-Sea Res. II 54, 1434–1447. http://dx.doi.org/10.1016/j.dsr2.2007.05.012.

Wong, G.T.F., Tseng, C.-M., Wen, L.-S., Chung, S.-W., 2007b. Nutrient dynamics and N-anomaly at the SEATS station. Deep-Sea Res. II 54, 1528–1545. http://dx.doi.org/10.1016/j.dsr2.2007.05.011.

Wong, G.T.F., Hong, H., Lin, S., Liu, H., Xue, H., 2011. Upwelling Ecosystem in the Southern Taiwan Strait. Cont. Shelf Res. 31, S1–S76.

Wong, G.T.F., Pan, X., Li, K.-Y., Shiah, F.K., Ho, T.-Y., Guo, X., 2015. Hydrography and nutrient dynamics in the Northern South China Sea Shelf-sea (NoSoCS). Deep-Sea Res. II. 117, 23–40.

Wu, M., Wong, G.T.F., Wu, Y.-C., Dao, M., 2015. Hydrogen peroxide in a sub-tropical shelf-sea: the northern South China Sea Shelf-sea (NoSoCS). Deep-Sea Res. II. 117, 143–154.

Xia, X., Yan, C.S., Liu, H., 2015. Dynamics of the bacterioplankton and diazotroph communities in the northern South China Sea by 454 pyrosequencing of the 16S RNA gene and *nifH* gene. Deep-Sea Research II. 117, 97–107.

Xu, J., Yin, K., He, L., Yuan, X., Ho, A.Y.T., Harrison, P.J., 2008. Phosphorus limitation in the northern South China Sea during late summer: Influence of the Pearl River. Deep-Sea Res. I 55, 1330–1342.

Xu, J., Yin, K., Ho, A.Y.T., Lee, J.H.W., Anderson, D.M., Harrison, P.J., 2009. Nutrient limitation in Hong Kong Waters inferred from comparison of nutrient ratios, bioassays and ^{33}P turnover times. Mar. Ecol. Prog. Ser. 388, 81–97.

Yin, K., Harrison, P.J., 2008. Nitrogen over enrichment in subtropical Pearl River estuarine coastal Waters: possible causes and consequences. Cont. Shelf Res. 28, 1435–1442.

Yin, K., Lin, Z., Ke, Z., 2004. Temporal and spatial distribution of dissolved oxygen in the Pearl River Estuary and adjacent coastal Waters. Cont. Shelf Res. 24, 1935–1948.

Zhang, J., 1995. Geochemistry of trace metals from Chinese River/estuary systems: an overview. Estuar. Coast. Shelf Sci. 41, 631–658.

Zhang, J., 1996. Nutrient elements in large Chinese estuaries. Cont. Shelf Res. 16, 1023–1045.

Zu, T., Gan, J., 2015. A numerical study of coupled estuary-shelf circulation around the Pearl River Estuary during summer: responses to variable winds, tides and River discharge. Deep-Sea Res. II. 117, 53–64.

George T.F. Wong*
Research Center for Environmental Changes, Academia Sinica,
128 Academia Road Section 2, Nankang, 115 Taipei, Taiwan
Institute of Ocean and Earth Sciences, University of Malaya,
Kuala Lumpur, Malaysia
E-mail address: gtfwong@gate.sinica.edu.tw

Teh-Lung Ku
Department of Earth Sciences, University of Southern California,
CA 90089, Los Angeles, United States

Hongbin Liu
Hong Kong University of Science and Technology, Hong Kong

Margaret Mulholland
Department of Ocean, Earth and Atmospheric Sciences,
Old Dominion University, Norfolk, VA 23508United States

---

* Corresponding author.