



## Abstract

In this special issue we examine the biogeochemical conditions and marine ecosystems in the major marginal seas of the western North Pacific Ocean, namely, the East China Sea, the Japan/East Sea to its north and the South China Sea to its south. They are all subject to strong climate forcing as well as anthropogenic impacts. On the one hand, continental margins in this region are bordered by the world's most densely populated coastal communities and receive tremendous amounts of land derived materials. On the other hand, the Kuroshio, the strong western boundary current, which is modulated by climate oscillation, exerts strong influences over all three marginal seas. Because these continental margins sustain arguably the most productive marine ecosystems, changes in these stressed ecosystems may threaten the livelihood of a large human population. This special issue reports the latest observations of the biogeochemical conditions and ecosystem functions in the three marginal seas. The studies exemplify many faceted ecosystem functions and biogeochemical expressions, but they reveal only a few long term trends mainly due to lack of long term records. It is critical to develop and sustain time series observations in order to detect biogeochemical changes and ecosystem responses in continental margins and to attribute the causes for better management of the environment and resources in these marginal seas.

## 1 Introduction

Continental margins in the western North Pacific Ocean are distinguished by the strong western boundary current, namely, the Kuroshio, and its intense interactions with the three marginal seas, namely, the South China Sea (SCS), East China Sea (ECS) and Japan/East Sea (JES, aka EJS). Among the three, the SCS and ECS receive voluminous runoffs from some of the largest rivers in the world, while the SCS and JES have very deep basins making them like miniature oceans. The complicated environmental

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settings provide the three marginal seas with a high diversity of habitats, which may nurture rich ecosystems and sustain very active biogeochemical processes.

Biogeochemistry and ecosystems in the three marginal seas are sensitive to atmospheric forcing and land-to-ocean fluxes (e.g., Tseng et al., 2011; Gong et al., 2011; Kim et al., 2011). The densely populated coastal zones in this region exert intense anthropogenic stressors that may alter the biogeochemical cycles and threaten the wellbeing of marine ecosystems (e.g., Cai et al., 2011). Moreover, the altered biogeochemical cycles may cause unknown feedbacks that could exacerbate the effects of climate change.

This special issue on “Biogeochemistry and ecosystems in the western north Pacific continental margins under climate change and anthropogenic forcing” reports on the biogeochemistry and ecosystems, how they interact with each other and how they respond to climate drivers and multiple anthropogenic stressors in the three marginal seas. Such understanding will better prepare our societies in facing the potentially adverse effects occurring in the changing continental margins. We first describe the environmental settings of the three marginal seas and then highlight notable findings in five topical areas:

1. Increasing atmospheric CO<sub>2</sub> and changing carbonate chemistry
2. Regional biogeochemical processes
3. Continental margin biota and their ecological characteristics
4. Physical forcing and biogeochemical responses
5. Ecosystem responses to external forcing

## 2 Environmental settings

All three marginal seas are significantly affected by the Kuroshio, which is the strong western boundary current in the North Pacific Ocean originating from a bifurcation of

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the North Equatorial Current to the east of the Luzon Island (Fig. 1). It flows northward off the eastern coast of Luzon and Taiwan, and along the shelf edge of the East China Sea and then turns eastward southwest of Kyushu. Along the way the Kuroshio or its branches intrude into all three marginal seas, first the SCS, then the ECS, and finally the JES, bringing strong influences on the hydrographic and biogeochemical properties. The two-way exchanges with the South and the East China Seas also result in significant modification of the Kuroshio water properties (Liu et al., 2010a, b).

The SCS, which spans from 1.5° N to 23° N, is located in tropical southeast Asia (Fig. 1). It has a total area of 3.35 million km<sup>2</sup>; 40.5% of it is the shelf, defined as regions with bottom depths less than 100 m, and the rest is the interior, where the depth attains a maximum of 5006 m (Liu et al., 2010b). The surrounding land masses and islands make the SCS a semi-enclosed water body. It is connected to the West Philippine Sea (WPS) through the Luzon Strait between Taiwan and Luzon, which has an effective sill depth around 2000 m and serves as the only channel for exchange of deep water with the ocean outside. The SCS is connected with the Sulu Sea (Fig. 1) mainly through the Mindoro Strait (with sill depth at 420 m). The Taiwan Strait and the Karimata Strait are rather shallow (ca. 60 m) and so allow only limited exchanges of waters with the East China Sea to the north and the Java Sea to the south (Fig. 1). The many channels and passages between the SCS and its surroundings make the water exchange rather efficient with an estimated residence time of about 50 yr for the basin water.

The ECS spans between China and the Ryukyu Islands with Taiwan as its southern bound and the Yellow Sea (YS) and Bohai Sea (BS) as its northern neighbor (Fig. 1a). The ECS together with the YS and BS forms one of the largest contiguous continental shelves in the world. The total area of the shelf down to the isobath of 200 m is about 1 million km<sup>2</sup> with an average depth of 63 m (Liu et al., 2010a). Seaward from the continental shelf is the Okinawa Trough (just to the north of the Ryukyu Islands as shown in Fig. 1), which extends from Kyushu to Taiwan with a maximum depth around 2000 m. The ECS is connected to the JES through the Tsushima/Korean Strait (T-K St.) to the

northeast, and connected to the Pacific Ocean through the Tokara Strait and many gaps in the island chain to the east.

The JES (Fig. 1) is a semi-enclosed marginal sea with only four narrow and shallow (< 150 m) straits connected to outer seas whereby its water exchange is fairly restricted (Kang et al., 2010). However, it is a rather deep marginal sea, with an average depth of about 1700 m and exceeding 3700 m in deeper places. Thus the interior of the JES is virtually isolated from the Pacific and this imposes unique characteristics which will be introduced further below. The JES covers an area about  $10^6$  km<sup>2</sup>. Its topographic features are summarized as consisting of three basins: the Japan Basin, the Ulleung Basin, and the Yamato Basin.

## 2.1 External forcings

All three marginal seas experience the southerly monsoon from May to August and the northerly monsoon from October to March of the next year. The winter monsoon is usually stronger than the summer monsoon. They are frequently invaded by typhoons with the SCS subject to the most invasions. From 1950 to 2001 there were on average 10 typhoons invading the SCS every year (<http://jtwccd.n.appspot.com/JTWC/>). Most typhoons occurred to the north of 10° N from May to October. Typhoons usually bring a considerable amount of rain to the region.

Both the SCS and the ECS shelf receive large riverine discharges of water and suspended sediments (Liu et al., 2010a). Changjiang (aka Yangtze River), which has an estimated average discharge of  $928 \text{ km}^3 \text{ yr}^{-1}$  to the ECS, is by far the largest source of riverine discharge. Secondary to Changjiang, the Mekong River and the Pearl River discharge 470 and  $300 \text{ km}^3 \text{ yr}^{-1}$ , respectively, to the SCS. The ECS and the SCS receive about the same amount of total runoff of  $1300 \text{ km}^3 \text{ yr}^{-1}$ , which carries huge amounts of suspended sediments and nutrient loads in both cases (Liu et al., 2010a, b).

Aside from river discharges all three marginal seas receive sizable contributions of macro- and micro-nutrients via dry and wet depositions from the atmosphere (e.g., Kim et al., 2011; Wang et al., 2012). The sources of the Aeolian fluxes are dusts and

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aerosols from industrial or biomass burning sources (Hsu et al., 2009; Lin et al., 2007, 2009).

## 2.2 Circulation and hydrography

The Kuroshio (Fig. 1a) to the east of the Luzon Island has an estimated transport of 14–16 Sv (Liu et al., 2010a). As the Kuroshio flows northward passing the Luzon Strait, its path makes a slight detour intruding into the SCS with only a small fraction (2–4 Sv) actually entering the interior, mostly during winter. Passing by the east coast of Taiwan, the Kuroshio enters the ECS with a mean transport of 21.5 Sv entering the ECS. As it encounters the shelf edge of the ECS, the Kuroshio turns northeastward following the isobaths, and separates from the shelf and flows around the southern tip of Kyushu. The Kuroshio transport in the ECS ( $23.7 \pm 2.0$  Sv, Ichikawa and Beardsley, 1993) is similar to that observed off Taiwan. Clearing of the Tokara Strait, the Kuroshio enters the open Pacific Ocean becoming the Kuroshio Extension, which is characterized by extensive meandering and recirculation (Qiu, 2002).

The currents within the SCS are rather weak with changing directions in responses to the forcing of alternating monsoons (Fig. 1), which drive a cyclonic gyre in winter and a reversed circulation in summer (Shaw and Chao, 1994; Chen et al., 2012). Aside from the Kuroshio intrusion in the upper water column through the Luzon Strait, the deep and intermediate water inflows induce a basin wide upwelling (Chao et al., 1996). The net inflow is balanced by outflow through other channels, including the Taiwan Strait and the Mindoro Strait in the north and the Karimata Strait in the south. The southern outflow forms the so-called SCS throughflow, which interacts with the Indonesian throughflow (Gordon et al., 2012).

Passing by Taiwan, the Kuroshio branches off in several places along the ECS shelf break, most notably to the northeast of Taiwan and to the southwest of Kyushu. Off northeastern Taiwan, the intruding Kuroshio water forms a cyclonic eddy in the surface layer with the subsurface water onwelling along the slope and shelf bottom (Liu et al., 1992a, b) and some shelf water veering off the shelf. Therefore, this is a region of active

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exchange of water and geochemical materials between the shelf and the open ocean. The intruding KBC combined with the northward flow from the Taiwan Strait forms the Taiwan Warm Current (Ichikawa and Beardsley, 2002). There is a persistent northward flow near the bottom through the Taiwan Strait from the SCS, while the surface flow is normally northward but changes direction when the northerly wind is strong and persistent in winter.

Southwest of Kyushu, the Kuroshio Branch Current intrudes onto the shelf to form the Tsushima Current flowing towards the Tsushima/Korea Strait (Fig. 1). In summer the Taiwan Warm Current also contributes to the Tsushima Current (Ichikawa and Beardsley, 2002). In winter (Fig. 1), the intruding Kuroshio Branch Current is the main source of the Tsushima Current, and also feeds into the Yellow Sea Warm Current (YSWC, Lie et al., 2001).

Dispersal of the Changjiang discharge varies seasonally (Lee and Chao, 2003). Normally the Changjiang freshwater discharge should drive a southward coastal jet, but, forced by the southwest monsoon in summer, the plume becomes diffuse and disperses towards the east or northeast and may enter the JES. Under the northerly monsoon in winter (Fig. 1), the plume follows a narrow coastal jet, extending southward (Lee and Chao, 2003), which is often named the China Coastal Current (CCC).

There are four major currents in the JES (Senju, 1999), namely, the Tsushima Warm Current (TWC), the East Korean Warm Current (EKWC), the Liman Current (LC) and the North Korean Cold Current (NKCC) (Fig. 1). The Tsushima Warm Current is the only significant source of water inflow to the JES. Unlike the other two marginal seas, river discharges are not important to the JES. The saline Tsushima Warm Current flows over the colder and less saline waters of the homogeneous Proper Water and out to the Pacific through the Tsugaru and Soya Straits. The north-flowing warm water forms a strong zonal polar front around 40° N against the south-flowing North Korean Cold Current (Fig. 1).

Recent studies (e.g., Kang et al., 2010) clearly indicate that the JES has undergone a dramatic change in the last 50 yr possibly due to climate forcing. The dissolved

oxygen concentration in the deep Japan Basin has decreased significantly since the 1930s, and the oxygen minimum has been deepening successively since the late 1960s.

### 3 Highlights of findings

#### 3.1 Increasing atmospheric CO<sub>2</sub> and changing carbonate chemistry

The CO<sub>2</sub> partial pressure in the surface water has been carefully studied in all of the marginal seas examined in this special issue. Kim et al. (2014) reported the repeat observations in the Ulleung Basin. Chou et al. (2013a) contrasted the different seasonal patterns of  $p\text{CO}_2$  in the ECS in the 1990s and the 2000s. Zhai et al. (2013) surveyed the entire SCS over 6 yr to assess the air-sea CO<sub>2</sub> exchange fluxes. They concluded that most of the SCS is a source of CO<sub>2</sub> to the atmosphere while the Pearl River Estuary zone is a slight sink, the overall SCS being a net source of CO<sub>2</sub> to the atmosphere. We have compiled time series of  $p\text{CO}_2$  in surface water at a few representative sites of the three marginal seas (Fig. 2) and conducted regression analysis to determine the trends (Table 2).

Following the increasing CO<sub>2</sub> partial pressure in the air, the JES and the SCS have shown clear increasing trend of  $p\text{CO}_2$  in the surface water (Table 2), while the trend in the ECS is unclear due to the complex situation there, including the strong impact of the Changjiang discharge on the biogeochemical processes of the ECS. The observed  $p\text{CO}_2$  in the Ulleung Basin yield a rather large increasing trend with very large uncertainty due to the strong seasonal variation (Table 2). Using a sophisticated data processing technique to delineate the seasonal variation, Kim et al. (2014) obtained a moderately strong trend of  $2.7 \pm 1.1 \mu\text{atm yr}^{-1}$ . For the SCS, we have constructed a time series from observations from the SEATS time-series station (Tseng et al., 2007) and observations from Domain B in the northern SCS, which covers the SEATS station (Zhai et al., 2013). The two datasets show good agreement for the



5 observations in 2003. The composite time series shows a strong increasing trend of  $3.2 \pm 1.4 \mu\text{atm yr}^{-1}$ . Both trends are significantly stronger than the increasing trend of  $p\text{CO}_2$  in the air ( $1.95 \mu\text{atm yr}^{-1}$ ) observed at Mauna Loa (Table 2) or that in the surface water ( $1.82 \pm 0.07 \mu\text{atm yr}^{-1}$ ) observed at the HOT station in the central Pacific (Rhein et al., 2013). The faster increasing trends in the marginal seas probably induce the decreasing capacity of  $\text{CO}_2$  storage in the more confined water bodies of the marginal seas, which warrant further investigation.

10 Chou et al. (2013a) reported dramatic changes in the seasonal patterns of  $p\text{CO}_2$  variation in the East China Sea, reflecting the complicated controlling factors. In contrast to the general increasing trend of  $p\text{CO}_2$ , the observed  $p\text{CO}_2$  in the Changjiang plume in summer appeared to have shown a decrease, which is attributed to the enhanced  $\text{CO}_2$  uptake by phytoplankton due to the increasing load of riverine nutrients. Subsequent to the phytoplankton bloom, water column respiration led to the elevated  $p\text{CO}_2$  in the surface water in autumn. Contrary to the consistent trends of  $p\text{CO}_2$  increase in the JES and SCS, the monthly average  $p\text{CO}_2$  values of the whole ECS derived for the period from 1998 to 2012 (C. M.Tseng et al., 2014) does not show a significant trend (Fig. 2). The aforementioned dramatic changes induced by the highly variable Changjiang discharge probably have masked the long term  $p\text{CO}_2$  trend.

20 Aside from driving unusual changes in  $p\text{CO}_2$ , the eutrophication induced algal bloom in the Changjiang outflow region also spurred extreme conditions of carbonate saturation ( $\Omega$ ). Chou et al. (2013b) observed very high aragonite saturation ( $\Omega_a$ ) values, up to 5.8, in the surface water off the Changjiang river mouth in summer, but very low  $\Omega_a$  values, as low as 1.7, in the bottom water beneath the plume. Figure 3 shows the wide range of  $\Omega_a$  values in the bottom water of the ECS (Chou et al., 2013b), which reveal a strong negative correlation with the concentration of dissolved inorganic carbon (DIC). Such a trend is consistent with the notion of exacerbation of acidification by eutrophication (Cai et al., 2011). In winter the range of  $\Omega_a$  was considerably smaller with minimum value above 2, apparently resulting from cooling and water column over-  
25 turning.

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Even lower degree of aragonite saturation (Fig. 3) has occurred in the bottom water of the YS (Zhai et al., 2014). The data points shown in Fig. 3 are the areal mean values, which show the lowest  $\Omega_a$  values around 1.4 observed in autumn and winter, while the lowest individual value (1.13) occurred in October 2011. Contrary to observations in the ECS, the YS showed the lowest values in autumn instead of summer. Zhai et al. (2014) attributed the lowest aragonite saturation to the cumulative effect of respiration in the bottom water of the YS. However, there are no reported values in autumn for the ECS so that we cannot rule out the possibility that the lowest value there may also occur in autumn. It is noteworthy that the acidification in the bottom waters of both areas are enhanced by high productivity, probably related to eutrophication. Although the total riverine supply of DIN to the Bohai-Yellow Sea is considerably less than that to the ECS according to the compilation of Liu et al. (2010a), the observed aragonite saturation values in the YS are lower than most observed in the ECS (Fig. 3). This probably reflects the difference in shelf water residence time of the two areas. For the combined Bohai-Yellow Sea, the water residence time is estimated to be 1.7 yr (Lee et al., 2004), whereas the southern ECS, south of the Changjiang river mouth, has an estimated residence time of about 0.5 yr or less (Liu et al., 2010a). The longer residence time would enhance the accumulation of DIC from respiration, which may explain the lower values in the YS.

### 3.2 Regional biogeochemical processes

Because estuaries and coastal regions are the most biogeochemically-active zones, particularly in regions with rapid economic development and population growth (Jennerjahn, 2012), we have constructed a schematic diagram to illustrate the major biogeochemical features in the estuary-shelf-boundary current system (Fig. 4). Many findings reported in this special issue are presented in this figure, which is modified and amended following the diagrams of Y.-F. Tseng et al. (2011, 2014) and Cai and Lohrenz (2010).

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In the Changjiang estuary and its outflow region in the East China Sea, the two papers by Hung et al. (2013) and Hsiao et al. (2014) describe the fate and importance of the mix of terrigenous and marine particles in the continental shelf area. Hung et al. (2013) describe the particulate flux of organic carbon from the sea surface to the bottom as measured by sediment traps during summer. One major caveat of these measurements on continental shelves is sediment resuspension (Fig. 4), because it modifies the export flux and its chemical composition. Hung et al. (2013) use a resuspension model, which is able to provide an estimate of the resuspended fraction collected in sediment traps. This fraction amounts from 27–93 % of the total flux. Vertical POC fluxes range from  $60 \text{ mg C m}^{-2} \text{ d}^{-1}$  in the outer shelf to  $785 \text{ mg C m}^{-2} \text{ d}^{-1}$  in the inner shelf. The high POC fluxes in the inner shelf supports the notion mentioned earlier that high respiration rate sustained by local supply of organics causes the low aragonite saturation in the bottom water. This is a first attempt to correct resuspension in sediment trap fluxes in the ECS and more tracer studies should be performed in order to better characterize resuspension and thus vertical fluxes.

Hsiao et al. (2014) have concentrated on the Changjiang River plume and nitrification processes, which convert ammonium to nitrate. This process consumes oxygen in the reaction which may contribute to hypoxia in eutrophicated regions (e.g. Pearl River, Dai et al., 2006). Nitrification rates are correlated to ammonium concentration with a peak at salinity 29 and are larger in bulk water than particle free-water. Furthermore, when compared to community respiration, a measure of total oxygen consumption in a sample of water, it is shown that a significant share of oxygen consumption is used by nitrification process. In half of the case, this share exceeds the Redfield ratio (23 %) and in three occasions exceeds 100 % (up to 318 %). This is only possible if other oxidants can be used for nitrification (such as Mn or Fe oxides). These are abundant in the turbid plume of the Changjiang and deserve more attention in order to understand nitrogen cycling in turbid estuaries (Fig. 4).

On a smaller scale in the northwestern SCS, Li et al. (2014) studied the nutrient dynamics in a number of rivers and estuaries on the east coast of the Hainan Island. They

found that all rivers are enriched of dissolved inorganic nitrogen relative to phosphate, due to high nitrate input. Based on a steady-state box model, riverine and groundwater inputs, with additional input from aquaculture effluents, were the major sources of nutrients to the east coast of the Hainan Island.

5 For the open SCS, Yang et al. (2014) estimate the fluxes of nitrate and ammonium in atmospheric deposition at a remote island (Dongsha) in the northern SCS and examine the potential sources of deposited nitrate from its dual isotopic composition ( $\delta^{15}\text{N}_{\text{NO}_3}$  and  $\delta^{18}\text{O}_{\text{NO}_3}$ ) in different seasons. It is interesting to evaluate possible impacts of atmospheric nitrogen deposition to nutrient budget in this region. Their measurements suggest that the majority of atmospheric deposition of reactive nitrogen was sourced from mainland China driven by the prevailing winter monsoon, whereas contributions from tropical cyclones and southeastern Asian biomass burning could be significant in summer. This is evidenced by the dual isotope ratios in atmospheric deposition. They estimate annual total atmospheric inorganic nitrogen deposition of  $\sim 50 \text{ mmol N m}^{-2} \text{ yr}^{-1}$ , stimulate a new production of  $\sim 330 \text{ mmol C m}^{-2} \text{ yr}^{-1}$ . Then they propose that this potential  $\text{CO}_2$  uptake would mitigate  $\sim 50\%$  of the  $\text{CO}_2$  release from the northern SCS. Although considerable uncertainties arose due to the lack of separation between the flux-weighted average  $\delta^{15}\text{N}$  of nitrate and the isotopic signal from  $\text{N}_2$  fixation, this finding demonstrates that atmospheric deposition may serve as an important external supplier of reactive nitrogen to the SCS.

20 Shang et al. (2013) examine the question of how different chlorophyll products from the MODIS satellite compare to each other and how consistent they are in revealing temporal and spatial patterns in the SCS. This is an important question, especially for optically complex coastal waters in near-shore regions where the accuracy of satellite-derived chlorophyll estimates is likely lower than in the open ocean, because chlorophyll is often not the dominant constituent influencing optical properties. Shang et al. (2013) compare products from three different algorithms that are routinely made available to the oceanographic community by NASA and find that all three algorithms capture essential features such as winter peaks in chlorophyll and summer bloom as-

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sociated with the plume of the Pearl River, but differ in the magnitude of these signals; as expected particularly large deviations occur in near-shore waters. Sheng et al.'s analysis also suggests significant uncertainties in the study region when compared to in situ measurements from the SEATS time series station, but find that regional tuning of the algorithms can improve the chlorophyll estimates.

### 3.3 Continental margin biota and their ecological characteristics

The two major pathways for energy and material flows in lower trophic levels of pelagic ecosystems are the grazing food chain and the microbial food web (e.g., Azam et al., 1983; Landry, 2002). The latter is based on bacterial uptake of dissolved organic carbon (DOC), which may be provided by primary production or by external sources, such as river discharge. Lai et al. (2014) conducted two summer cruises in the northern SCS and found evidence to support the malfunctioning microbial-loop hypothesis proposed by Thingstad et al. (1997) that DOC accumulation occurs when bacterial production was low. In contrast to the short DOC turnover time of 37–60 days observed in the inner shelf near the Pearl River mouth, it was more than 100 days in the outer shelf and basin region, where the inorganic nutrients were depleted and no correlations were found among bacterial production (BP), DOC and primary production (PP) in the shelf-to-basin transition zone (Fig. 4). Inside the mid-shelf (bottom depth <100 m), where inorganic nutrients were abundant, BP, DOC and PP were positively inter-correlated. The availability of limiting minerals could affect the couplings/decouplings between the source (i.e. phytoplankton or riverine supply of DOC) and sink (i.e. bacteria) of organic carbon. This implies that the estuaries and river outflow regions may become more heterotrophic in the future due to increasing anthropogenic nutrient loads, which enhance DOC consumption.

Since microbial food web composed by protists is likely functioning regardless of the seasons and areas, it is important to biogeochemical cycles and trophic dynamics in pelagic food webs (e.g., Shinada et al., 2001). Tsai et al. (2013) evaluated the impacts of viral lysis and nanoflagellate grazing on bacterial production in the ECS. They

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demonstrated that viral lysis was similar or more important than protozoan grazing for the dynamics of bacterial community. As significantly biogeochemical and ecological impacts have been emphasized for marine viruses (Fuhrman, 1999), trophic dynamics in microbial food web might be revised by including viruses.

5 On the other hand, phytoplankton growth and mortality are major drivers of biogeochemical cycles and material flow in pelagic food web. Guo et al. (2014) studied the growth and grazing rates of different picophytoplankton populations in the ECS, in an attempt to understand the interactive mechanism of bottom-up and top-down control in regulating picophytoplankton biomass and composition, and consequently the dynamics of biogeochemical cycling of carbon in the subtropical marginal seas. For the northern SCS, B. Chen et al. (2013) compared growth and grazing mortality of phytoplankton community in different depths, seasons and sites using in situ experiments. While microzooplankton grazing was equivalent to more than half of the daily primary production as estimated before (Calbet and Landry, 2004), they were largely variable and decoupled by physical disturbances. The decoupling between growth and mortality may be the results of non-steady state condition due to physical forcing and food web complexity, which makes it difficult to predict the grazing mortality at global scales.

10 Chang et al. (2013) assumed that allometric scaling of phytoplankton cell size of natural assemblage to growth and mortality could be described by the metabolic theory of ecology (MTE). While their experiments in the ECS did not support the MTE, they suggested that the higher grazing impacts of large phytoplankton cells release the grazing mortality of small phytoplankton cells. Metazoans are connecting grazing and microbial food webs through their feeding on phytoplankton and protozoans (e.g., Kobari et al., 2003), suggesting that metazoan growth is an integration of production at lower trophic levels. Similarly to Chang et al. (2013), Lin et al. (2013) tested the MTE for copepod community in the ECS. The results from their experiments generally agreed with the MTE because growth rates of copepod community showed positive correlations with ambient temperature and negative to their body size. These findings suggest trophic interactions among the components are important for biological process of the pelagic

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ecosystems even in areas, such as the ECS where the main drivers are external forcing, like the Asian monsoon and Kuroshio.

### 3.4 Physical forcing and biogeochemical responses

The northern ECS is an important spawning and nursery ground for many species of fish and squid. Umezawa et al. (2014) use  $\delta^{15}\text{N}_{\text{NO}_3}$  and  $\delta^{18}\text{O}_{\text{NO}_3}$  and T-S relationship to investigate the significance of different nitrate sources in contributing to the nutrient pool and sustaining phytoplankton growth in this region. In winter, Kuroshio Subsurface Water (KSSW) and the Yellow Sea Mixed Water (YSMW) predominantly contributed to the DIN pool in the shelf water, while the warm Kuroshio Surface Water seemed to stimulate phytoplankton growth in the Okinawa Trough with nutrient supplied from the KSSW. In summer, Changjiang discharge, Yellow Sea Cold Water Mass (YSCWM), and KSSW affected the distribution and abundance of nitrate in the northern ECS. The relative importance of the former two depended on precipitation in the Changjiang drainage basin and the development of the YSCWM in the shelf bottom water. Aside from oceanic and riverine sources atmospheric deposition or nitrogen fixation could also have supplied nitrogen to the region as implied by some relatively low  $\delta^{15}\text{N}_{\text{NO}_3}$  values observed in the shelf water. They were lower than expected from isotope fractionation during nitrate uptake. The Kuroshio is the most important nutrient supplier in the western North Pacific Ocean. Based on the absolute geostrophic velocity, which was calculated from the repeated hydrographic data, and nitrate concentration measurement across five sections along the Kuroshio downstream during at least the last decade, Guo et al. (2013) computed the nitrate transport by the Kuroshio Current from the ECS to south of Japan. Their estimated net nitrate transport crossing the PN line within the Okinawa Trough (Fig. 1) is  $178.8 \text{ kmols}^{-1}$ , which is larger than that ( $156.3 \text{ kmols}^{-1}$ ) downstream through the Tokara Strait (Fig. 1). This is consistent with the notion that, in the region southwest of Kyshyu, the Kuroshio feeds the Kuroshio Branch Current, the Tsushima Current and the Yellow Sea Warm Current, which transport nutrients to the ECS, Yellow Sea and the JES. A weak but deep

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Ryukyu Current contributes to the nitrate transport of the same order as the strong but shallower Kuroshio within the Okinawa Trough along the shelf break of the ECS (Fig. 1). The nitrate flux at every section shows a subsurface maximum core (Fig. 4), which indicates the presence of a stable nutrient stream along the Kuroshio from the East China Sea to south of Japan. The mean nitrate transport of the Kuroshio along 137° E, more downstream from the Tokara Strait, is significantly enhanced reaching an estimated value of  $\sim 1000 \text{ kmol s}^{-1}$ , which is comparable to the Gulf Stream transport (Pelegrí and Csanady, 1991; Pelegrí et al., 1996, 2006; Williams et al., 2011). Guo et al. (2013) conclude that the Kuroshio recirculation has a significant contribution to the downstream increase of nitrate transport as occurred along the Gulf Stream (Williams et al., 2011). This is the first attempt to analyze nutrient and water mass transports in this region.

The rather rich nutrient reserve in the ECS shelf water could serve as a sizable nutrient supply to the oligotrophic northern SCS in winter as suggested by Han et al. (2013). Based on field observations covering both the ECS and the northern SCS, they examined southward long-range transport of nutrients from the ECS to the northeastern SCS carried by the China Coastal Current (CCC) driven by the prevailing northeast monsoon in winter. They estimated a DIN transport of  $1430 \pm 1024 \text{ mol s}^{-1}$  by combining the field observation of DIN distribution and their estimate of volume transport of the CCC based on both observation and modeling. The redistribution of DIN probably had little effect on the productivity of the ECS, which is not nutrient limited in winter, but may have major impact on the northern SCS shelf, where the water temperature was favorable and river-sourced nutrients were limited. Under the assumption that DIN was the limiting nutrient, such southward DIN transport could have sustained a total carbon fixation of  $8.84 \pm 6.33 \times 10^{11} \text{ g C}$  by phytoplankton, which accounts for 14–22 % of PP in winter in the shelf region to the north of the Pearl River mouth. It is noted that the estimated DIN transport, which is at  $\sim 1 \%$  level of that carried by the Kuroshio in the ECS, exceeded the total DIN discharge from rivers in winter by a factor of two (Han



et al., 2013), indicating that additional supply of DIN could have come from oceanic sources discussed above.

It is well known that the variability of surface chlorophyll concentrations in the SCS basin is related to wind forcing, especially during winter monsoon, which leads to a pronounced seasonal cycle in chlorophyll (Liu et al., 2002). Liu et al. (2013) show that after removing the seasonal cycle, surface chlorophyll responds asymmetrically to wind forcing under El Niño or La Niña conditions. For this purpose Liu et al. (2013) produced a time series of satellite-derived chlorophyll for a location in the central northern SCS surroundings the South-East Asian Time-series Study (SEATS) station by merging SeaWiFS and MODIS products in this region and validating it against in situ chlorophyll data from SEATS. Under El Niño conditions surface chlorophyll is strongly correlated with wind forcing, while under La Niña conditions the correlation is weak (Liu et al., 2013). The weak correlation during La Niña is explained by the deeper thermocline due to weakened SCS throughflow, which diminishes the importance of wind-driven nutrient pumping.

Aside from affecting the basin-wide upwelling the intrusion of the Kuroshio into the SCS has more direct consequences as demonstrated by Du et al. (2013). They used an isopycnal mixing model to quantify the extent of the Kuroshio intrusion and its impact on the nutrient inventory in the northern SCS. Results show that the nutrient inventory in the upper 100 m of the northern SCS is overall negatively correlated to the Kuroshio water fraction, because the Kuroshio surface water is depleted in nutrients. Consequently, the Kuroshio intrusion has complicated and significant influences on nutrient distribution in the SCS and its seasonal variation.

### 3.5 Ecosystem responses to external forcing

In the study area of this special issue, external forcing, like the Changjiang River discharge, the East Asian monsoon and the Kuroshio, affects greatly and variously the pelagic ecosystems. The maintenance of high primary production in the Ulleung Basin of the JES has been explained by wind-driven coastal upwelling (Hyun et al., 2009;

Yoo and Park, 2009), mesoscale eddies, which are often associated with the branch currents of the Kuroshio (Hyun et al., 2009; Kim et al., 2012; Lim et al., 2012), and hydrographic conditions (Kwak et al., 2013a). Kwak et al. (2013b) measured the primary and new productivities in the UB throughout a year. The vertical structure of the water column in the basin is characterized by two distinct features: well-stratified in summer-fall and well-mixed in winter-spring. Nutrient distributions in euphotic zone show seasonal shift from oligotrophic to eutrophic. Diatoms were in general the most dominant phytoplankton. The annual primary, new, and regenerated production in the Ulleung Basin were  $273.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ ,  $62.6 \text{ g N m}^{-2} \text{ yr}^{-1}$ , and  $48.7 \text{ g N m}^{-2} \text{ yr}^{-1}$ , respectively. The observed high  $f$ -ratio (0.59) in the basin indicated the importance of nitrate as the predominant nitrogen source for primary production. Based on high levels of new production, they suggest that a large portion of the total annual primary production might potentially be exported from the diatom-dominated euphotic zone to a deeper zone in the Ulleung Basin. These findings support the conclusion that the Ulleung Basin can be considered as a biological “hot spot” in terms of high phytoplankton productivity and biological pump efficiency. It is noted that the average C/N uptake ratio found in this study was  $3.4 \pm 0.8$ , which is considerably lower than the Redfield ratio.

In contrast to previous studies on the primary production and chlorophyll *a* distribution based on weekly or monthly composites of satellite ocean color data, Son et al. (2014) reveals highly resolved temporal variation of biochemical properties of the upper layer of the Ulleung Basin in the southwestern JES. Time-series measurement of biochemical, optical, and physical parameters by an ocean buoy, UBIM (Ulleung Basin Integrated Mooring) during the spring transition, highlights an important role of advection of subsurface water mass (i.e. the East Sea Intermediate Water) in triggering the subsurface spring bloom below the surface mixed layer in the Ulleung Basin. Biochemical and colocated physical data suggest that the onset of subsurface spring phytoplankton bloom in the Ulleung Basin is closely associated with low-frequency modulation of the mixed layer depth determined by shoaling and deepening of isother-

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mal depths. Such a time-series measurement can give new insight into a mechanism that triggers the onset of the spring bloom in the Ulleung Basin.

For the ECS the study of C.-C. Chen et al. (2013) also reveals the dramatic changes before and after the spring transition period. They surveyed the ECS in Aprils of 2009 and 2010, and obtained contrasting results of community respiration (CR). In 2009 the CR ranged from 15.2–307.3 mg C m<sup>-3</sup> d<sup>-1</sup> with a mean of 111.7 ± 76.3 mg C m<sup>-3</sup> d<sup>-1</sup>; in 2010 CR ranged from 4.2–242.6 mg C m<sup>-3</sup> d<sup>-1</sup> with a mean of 50.7 ± 62.9 mg C m<sup>-3</sup> d<sup>-1</sup>. They attribute the contrast to the significant difference in phytoplankton biomass as indicated by the ranges and averages of sea surface chlorophyll-a concentration: 0.3–7.9 (1.8 ± 2.0) mg m<sup>-3</sup> in 2009 and 0.1–5.9 (1.3 ± 1.1) mg m<sup>-3</sup> in 2010. It is likely that the 2009 cruise was during the spring bloom, whereas the 2010 cruise was before the spring bloom or during its early stage. Although the Changjiang river discharge often stimulates algal bloom in the ECS (Gong et al., 2011), the authors note that the higher discharge in 2010 did not induce stronger algal growth. Instead they speculate that the temperature was the main control as indicated by the SST ranges and averages: 15.7–25.3 °C (19.4 ± 2.3 °C) in 2009 and 10.6–25.3 °C (16.9 ± 4.7 °C) in 2010.

Sun et al. (2014) describes the distribution of living coccolithophores in the YS and the ECS in summer and winter, and correlation between species and environmental parameters. As observed the living coccolithophores in surface layer occurred mainly in the coastal belt and the shelf region south of the Changjiang River mouth; in winter they were abundant in the continental shelf area along the PN line (Fig. 1). Spatial comparison indicates lower species diversity and less abundance in the YS than those in the ECS in both seasons. They suggest that temperature and the nitrate concentration may be the major environmental factors controlling the distribution and species composition of living coccolithophores. While this is little studied in other seasons, more studies on the seasonal distribution of coccolithophores should be pursued in the future, because coccolithophores take on major roles in the marine carbon cycle.

Focusing on the same area plus the BS, He et al. (2013) investigate long-term changes in the occurrence of phytoplankton blooms using a 14 yr time series of

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satellite-derived surface chlorophyll data. They obtain the spatially resolved time series of satellite chlorophyll by merging SeaWiFS and MODIS data and validating it against two in situ data sets from large cruises covering the ECS, YS and BS. By applying an algorithm for the identification of phytoplankton blooms, He et al. (2013) are able to analyze spatial and temporal patterns in bloom distribution. They find a doubling in bloom intensity in the YS and BS over the past 14 yr, which they attribute to a doubling in the supply of nitrate and phosphate primarily due to increased nutrient loads from the adjacent rivers. However, in the Changjiang outflow region in the ECS, they find no long-term change in bloom intensity in spite of the reported increase of Changjiang DIN load in the last few decades (Yan et al., 2010). This lack of long-term trend could be due to the same reason mentioned earlier for the lack of long-term trend of  $p\text{CO}_2$  in the ECS. It is likely that the high variability of water discharge from Changjiang, which controls the productivity as well as  $p\text{CO}_2$ , probably masks the long-term trend.

Although the Changjiang discharge provides ample amount of DIN to the receiving water body, the lack of proportional DIP load in the discharge may induce potential P-stress for phytoplankton. In order to address this issue, Y.-F. Tseng et al. (2014) conducted a cruise in the Changjiang plume during summer 2011 to survey distributions of nutrients, chlorophyll *a*, and bulk alkaline phosphatase activity (APA). Their observations reveal rather complicated situation with P-limitation in the area covered by the Changjiang Diluted Water. In the low salinity end of the plume, where DIN was enriched, high APA was found and its value was inversely related to chlorophyll, indicating its allochthonous origin, probably from limnetic heterotrophic bacteria. The negative correlation implies that phytoplankton growth was not P-limited. This is probably because coastal upwelling and entrainment of subsurface water associated with the moving river plume may bring phosphate rich Kuroshio Subsurface Water to the euphotic zone to fuel the algal growth. On the other hand, high APA in saline water at the fringe of the plume is a clear sign of P-stress associated with phytoplankton growth (Fig. 4). The strong stratification probably blocked diapycnal phosphate supply at the plume fringe. They conclude that phosphate supply instead of its concentration

is probably more important in determining the state of P-limitation, and, therefore, the expression of APA.

Over the entire ECS, Chen et al. (2014) found that abundance and community structure of larval fish assemblage changed between the two different monsoon seasons.

Under the northeast monsoon in winter, there were two assemblages, the inshore and the offshore assemblages. Under the southwest monsoon in summer, the coverage of the inshore assemblage shrank covering the northern part of the Changjiang River plume, and that of the offshore assemblage expanded, whereas a coastal assemblage occupied the southern part of the Changjiang River plume and the coastal belt further south. They suggested that larval fish assemblage showed higher biodiversity and abundance under the southwest monsoon.

#### 4 Summary and concluding remarks

The three major marginal seas in the western North Pacific Ocean, namely, the Japan/East Sea (JES), the East China Sea (ECS) and the South China Sea (SCS), are experiencing multiple stressors induced by anthropogenic as well as natural drivers. However, few long-term trends in their biogeochemical conditions or ecosystem functions can be determined mainly due to the lack of long-term observations. The only notable long-term biogeochemical trends are the increase of  $p\text{CO}_2$  in surface waters of the JES and the SCS, which are at significantly faster rates than that at the HOT station in the open Pacific Ocean, but no clear trend can be discerned in the ECS probably due to the high variability of the Changjiang discharge that masks the trend.

The only long-term trends in ecosystem function are the doubling of the algal bloom intensity in the Bohai Sea and Yellow Sea, which is attributed to increasing anthropogenic nutrient loads from river discharges. Despite the reported increasing DIN load in Changjiang no similar long-term trend was found in the ECS probably also due to the masking effect of the high variability of Changjiang discharge. On the other hand, eutrophication-induced high primary production in the ECS leads to unusually low pH

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and low aragonite saturation in the bottom waters beneath the Changjiang river plume in summer resulting from intense respiration. This notion is corroborated by the observed very high POC fluxes, up to  $785 \text{ mg C m}^{-2} \text{ d}^{-1}$  in the ECS inner shelf. Even though the algal bloom in the Yellow Sea (YS) is usually not as strong as that in the Changjinag plume, lower pH and aragonite saturation occurs in the bottom water of the in autumn probably due to a longer residence time of the bottom water. In the coastal region of the Hainan Island effluents from aquaculture are another human-induced nutrient source, in addition to river runoff and submarine groundwater discharge, that further elevates the nutrient level. Aside from high anthropogenic nutrient loads carried by water, human activities also contribute to the atmospheric deposition of air borne DIN, which is evidenced in the ECS and the SCS.

In the turbid Changjiang estuary and inner shelf, very high nitrification rates were associated with high concentrations of suspended particulate matter (SPM), which appears to support and enhance the microbial activities. The measured nitrification rates exceeded the values expected from oxygen consumption in half of the samples, suggesting that iron or manganese oxides associated with SPM could have served as oxidants for nitrification.

More important than the riverine supplies of nutrients, the Kuroshio is a powerful nutrient supplier in the western North Pacific Ocean. It carries a DIN load estimated at  $179 \text{ kmol N s}^{-1}$  with a subsurface core at 400 m depth in the Okinawa Trough. In parallel the Ryukyu Current carries a similar DIN load in the region east of the Ryukyu Island Chain. The two currents merge in the area southeast of Honshu with an enhanced recirculation resulting in a very strong DIN transport of  $\sim 1000 \text{ kmol N s}^{-1}$ . The Kuroshio Branch Currents along the shelf break of the ECS feed to the shelf the Kuroshio Sub-surface Water, which is identified by  $\delta^{15}\text{N}$  and  $\delta^{18}\text{O}$  values of nitrate as the most important nutrient source along with the Changjiang discharge, mainly in summer.

The Kuroshio Branch Current southwest of Kyushu feeds the Tsushima Current into the JES and becomes the Tsushima Warm Current. The frontal instability probably induces nutrient pumping via generation of eddies, which, along with wind driven coastal

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upwelling, render the Ulleung Basin a biological “hot spot” with very high primary and new productions. By contrast, the intrusion of Kuroshio into the SCS through the Luzon Strait brings nutrient-poor surface water that reduces the nutrient inventory in the northern SCS. On the other hand, the deep inflow into the SCS forms the SCS throughflow that controls the basin wide upwelling and nutrient supply. While the wind strength has a first order control over the sea surface chlorophyll due to wind-driven nutrient pumping, the efficiency of nutrient pumping is modulated by the position of the nutricline, which is controlled by the SCS throughflow. During La Niña events the throughflow is weaker resulting in a lowered nutricline, and, consequently, a less efficient wind-driven nutrient pumping. In the shelf region of the northern SCS, additional nutrient supply comes from the rich reserve in the ECS as a stream of nutrient load carried southward by the China Coast Current driven by the prevailing northeast monsoon in winter.

The potential P-limitation in the Changjiang plume due to the imbalance of the N/P ratio in Changjiang discharge is probably alleviated by the marine nutrient supply rich in phosphate facilitated by river plume-associated upwelling and entrainment. Severe P-limitation occurs in the outer rim of the river plume, where supply of phosphate from the subsurface water is suppressed. The contrast in nutrient regime in the inner and outer shelves in different seasons also controls the fish larvae assemblage in the ECS. Along the river-shelf-basin continuum of the northern SCS, the depletion of inorganic nutrients in the inner shelf sustains a tight coupling between primary production and bacterial production, resulting in fast turnover of dissolved organic carbon (DOC), whereas the nutrient depleted outer shelf and open sea witnesses decoupled PP and BP, leading to slow DOC turnover.

It has been increasingly recognized in recent years that time series observations are critical for detecting and attributing change and ecosystem response, especially in continental margins (Levin et al., 2014). One good example is the CARI-ACO time-series program in the Cariaco Basin (<http://imars.marine.usf.edu/cariaco/cariaco-ocean-time-series-program>). Its time-series observations reveals that in recent years the primary production and phytoplankton biomass have decreased because of



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decreased nutrient supply due to weakened upwelling caused by weakening of the trade wind in the tropical Atlantic Ocean related to climate shift (Muller-Karger et al., 2013). In response, the phytoplankton community structure has shifted from a diatom-dominated assemblage to one in which the pico- and nanoplankton are more abundant (Taylor et al., 2012). At the same time, zooplankton biomass has increased, which coincides with the collapse of the Spanish sardine (*Sardinella aurita*) fishery off Venezuela (Rueda-Roa, 2012).

Consequently, the existing time series programs in the marginal sea, namely, the EAST (East Asian Seas Time-series) program for the JES (e.g., Kang et al., 2003) and the The SEATS (South-East Asian Time-series Study) program for the SCS (Wong et al., 2007) should be sustained and expanded in scope, especially in ecosystem observations. For the ECS a program similar to the CalCOFI (California Cooperative Oceanic Fisheries Investigations) program (<http://www.calcofi.org/>) need be developed to detect any ecosystem changes that may jeopardize human wellbeing in the communities depending on its ecosystem services and to better manage the coastal environment and resources.

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**Table 1.** Abbreviations of geographic names and currents.

Abbr.	Geographic names	Abbr.	Current names
ECS	East China Sea	CCC	China Coastal Current
JB	Japan Basin	EKWC	Eastern Korean Warm Current
JES	Japan/East Sea	KBC	Kuroshio Branch Current
M St	Mindoro Strait	LC	Liman Current
SCS	South China Sea	NKCC	North Korean Cold Current
T-K St	Tsushima/Korean Strait	TWC	Tsushima Warm Current
Tw St	Taiwan Strait	YSWC	Yellow Sea Warm Current
UB	Ulleung Basin		
YB	Yamato Basin		
YS	Yellow Sea		

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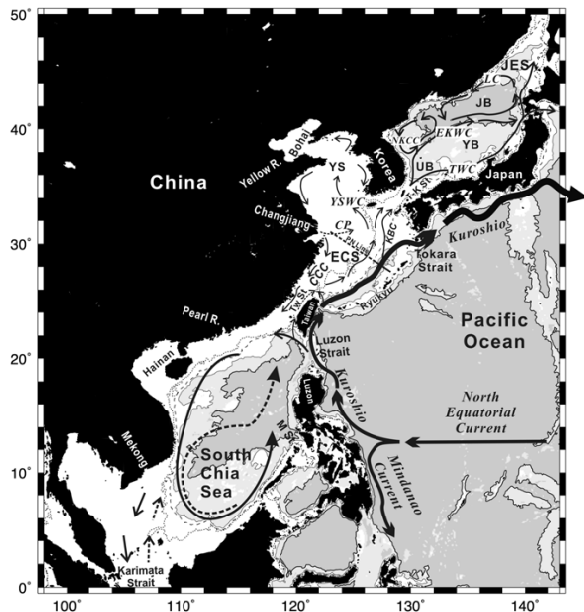
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**Table 2.** Trends of observed  $p\text{CO}_2$  in surface waters of the marginal seas. Also listed is that in the air from Mauna Loa for comparison.

Site	Period	Trend ( $\mu\text{atm yr}^{-1}$ )	$n$	$R^2$	$p$
JES	1995–2009	$3.9 \pm 2.2$ $(2.7 \pm 1.1)^{(1)}$	14	0.227	0.085
ECS	1998–2011	–	13	–	–
SCS	1999–2007	$3.2 \pm 1.4^{(2)}$	30	0.177	0.021
Mauna Loa	1994–2013	1.95	240	0.963	<0.001

Note: (1) The trend is obtained by simple linear regression of the observed values; that in parenthesis is determined by more sophisticated trend fitting (Kim et al., 2014). (2) The trend is obtained by linear regression of the observed values from the SEATS station (Tseng et al., 2007) and from Domain B of the northern SCS (Zhai et al., 2013).



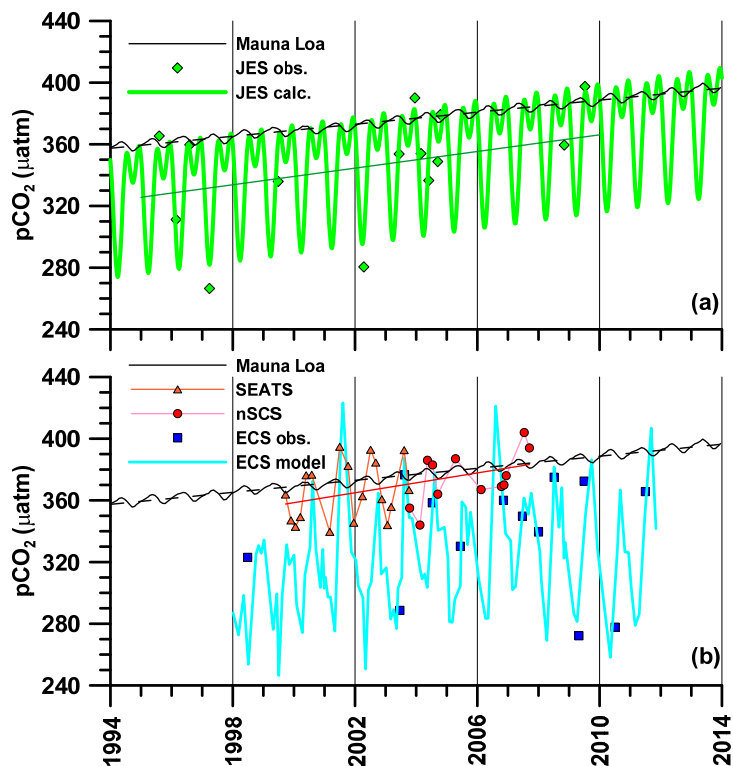
**Figure 1.** Marginal seas in the western North Pacific Ocean. The contours are isobaths of 100 m (dotted), 200 m (dashed), 1000 m (thin solid) and 3000 m (thick solid). Sea floor deeper than 3000 m is shaded in grey. The Kuroshio is the strong western boundary current that flows through this region and interact extensively with the three major marginal seas, namely, the South China Sea (SCS), East China Sea (ECS) and the Japan/East Sea. The ECS connects with the Yellow Sea, which in turn connects to the Bohai Sea, forming one of the largest contiguous continental shelves in the world. Four large rivers empty into the continental margins. The Mekong and the Pearl River discharge into the SCS; the Changjiang river discharges into the ECS forming a distinct large river plume (Changjiang plume, CP) in summer; the Yellow River discharges into the Bohai Sea. The circulations with the marginal seas change seasonally. The stronger winter monsoon usually drives stronger currents, which are shown in solid curves. However, the weaker summer monsoon does cause some changes in currents; the more notable ones are shown as dashed curves. See Table 1 for abbreviations.

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**Figure 2.** Observed partial pressure of  $\text{CO}_2$  in surface waters of the three marginal seas examined in this special issue, namely, **(a)** the Japan/East Sea (Kim et al., 2014), **(b)** the East China Sea (Tseng et al., 2014a) and the South China Sea (Tseng et al., 2007; Zhai et al., 2013). Also plotted are the  $p\text{CO}_2$  in the air observed at Mauna Loa, Hawaii. Both the JES and the SCS show clear trend of increasing  $p\text{CO}_2$ , while the ECS does not show a clear trend due to strong variability and insufficient measurements. (See text)

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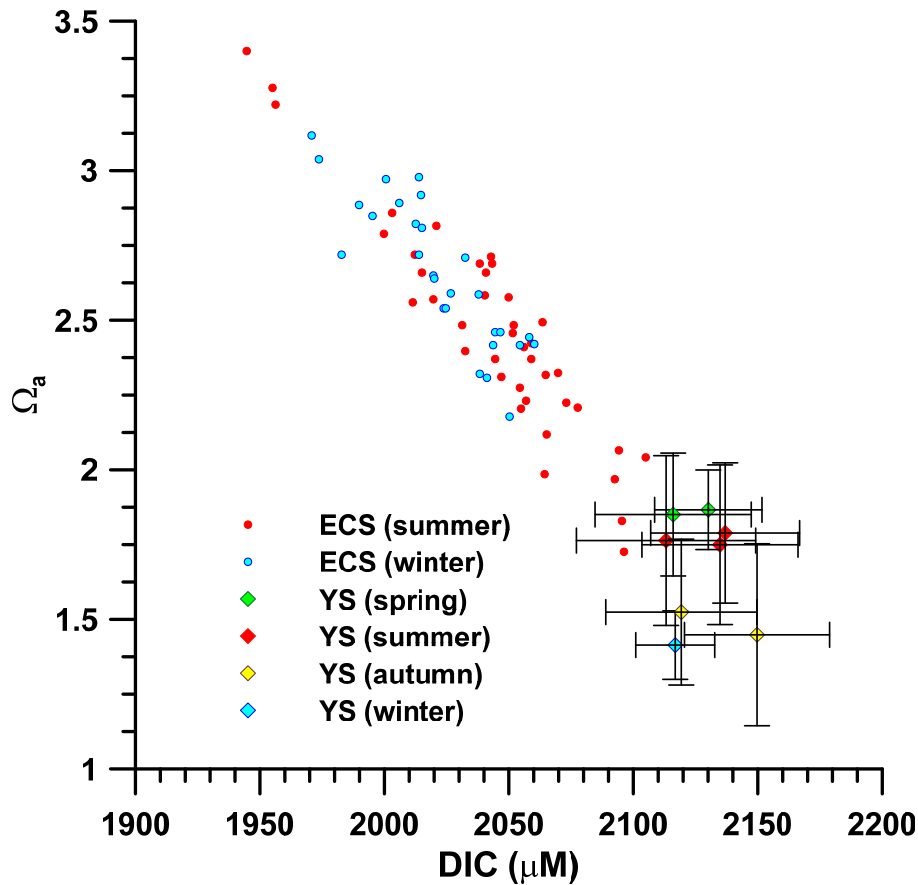
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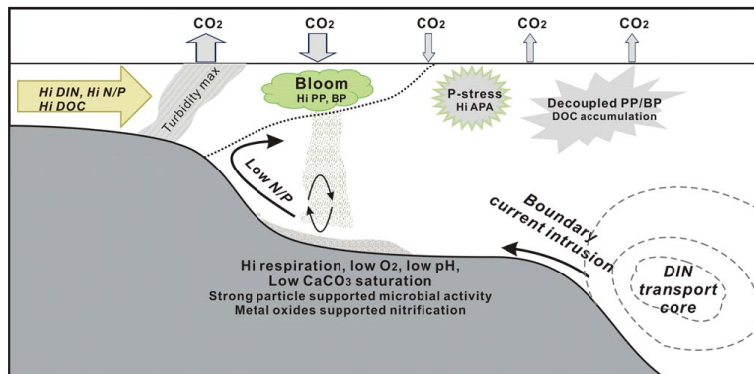
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**Figure 3.** Aragonite saturation ( $\Omega_a$ ) vs. DIC in the bottom waters of the ECS (Chou et al., 2013b) and the YS (Zhai et al., 2014). The data points of the YS are areal mean values from each cruise. The trend indicates the lowering of aragonite saturation in correspondence to increasing accumulation of DIC from respiration.



**Figure 4.** Schematic diagram showing the major biogeochemical features in the river-shelf-boundary current systems observed in studies of this special issue. Riverine nutrients induced phytoplankton bloom in the river plume draws down  $p\text{CO}_2$  (Chen et al., 2013) and produces high POC flux (Hung et al., 2013), which causes strong community respiration (Chen et al., 2013) probably driven by active resuspension (Hung et al., 2013). The elevated particle concentrations near the river mouth sustain exceptionally high microbial activities, which include nitrification processes facilitated probably by the particle borne metal oxides (Hsiao et al., 2014). Consequently, low oxygen, low pH and low aragonite saturation occur in the bottom water beneath the surface algal bloom in the Changjiang river plume and also in the YS (Chou et al., 2013b; Zhai et al., 2014). Although the riverine nutrient loads in the east Asia are often enriched in dissolved inorganic nitrogen (DIN) resulting in high N/P ratio, P-limitation does not happen in the river plume because of the nutrient supply with low N/P from the marine origin provided by upwelling and entrainment associated with the river plume (Tseng et al., 2014b). Instead P-stress occurs in the outer rim of the river plume and often induces high alkaline phosphatase activities (AKA). The nutrient supply from marine origin is often actuated by intrusion onto the shelf from boundary currents, such as the Kuroshio, which carries a large nutrient load with a subsurface core (Guo et al., 2013). In the inner shelf where nutrient is replete, primary production (PP) and bacterial production (BP) are tightly coupled driving a rapid turn-over of dissolved organic carbon (DOC), whereas, in the oligotrophic outer shelf, the two are decoupled and DOC tends to accumulate due to low turnover rate (Lai et al., 2014).

**Biogeochemistry and ecosystems of continental margins in the western North Pacific Ocean**

K.-K. Liu et al.

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