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The influence of episodic flooding on pelagic ecosystem in the East China Sea

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Running header: Effect of flooding in the East China Sea

ABSTRACT

This study was designed to determine the effects of flooding on pelagic ecosystem in the East China Sea (ECS), especially on plankton community respiration (CR). In July 2010, a flood occurred in the Changjiang River. As a comparison, a variety of both abiotic and biotic parameters were monitored, as well as in July 2009, a non-flooding period. During the flooding, the Changjiang diluted water (CDW) zone covered almost two thirds of the ECS, which was approximately six times that of the non-flooding period. The mean nitrate concentration was higher in 2010 (6.2 μM) than in 2009 (2.0 μM). However, during the 2010 flood, the mean values of Chl *a* and bacterial biomass were only slightly higher or even lower than in 2009. However, the CR was still higher in 2010 than in 2009, with mean values of 105.6 and 73.2 mg C m^{-3} d^{-1}, respectively. The higher CR in 2010 could be attributed to vigorous plankton metabolic activities, especially phytoplankton, at stations in the CDW zone, which were not characterized by low SSS in 2009. In addition, zooplankton might be another important component contributing to the high CR rate observed in 2010. Furthermore, there was a significant amount of fCO_2 drawdown in the 2010 flood. These results suggest that the flood in 2010 had a significant effect on the carbon balance in the ECS. This effect might become more pronounced in the future, as extreme rainfall events and flooding magnitudes are predicted to increase globally due to climate change.

Keywords: Bacteria; Dissolved inorganic nutrients; East China Sea; Phytoplankton; Plankton community respiration; Primary production; Yangtze River

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INTRODUCTION

Riverine run-off has a profound effect on the production of organic carbon and its consumption in coastal ecosystems (e.g., Dagg et al., 2004; Hedges et al., 1997 and references therein). Accompanying freshwater discharge, a substantial amount of dissolved inorganic nutrients is routinely delivered into coastal regions, thus enhancing primary productivity (PP; e.g., Dagg et al., 2004; Nixon et al., 1996). In addition, a large quantity of particulate and dissolved organic matter is discharged via riverine input (e.g., Wang et al., 2012). High rates of microbial metabolism associated with this discharge have been observed in marine environments at local scales (e.g., Hedges et al., 1994; Malone and Ducklow, 1990). River plumes can extend for hundreds of kilometers along the continental shelf, as in the case of the Amazon River (e.g., Müller-Karger et al., 1988). Overall, the effects of river plumes on coastal ecosystems are strongly related to the volume of freshwater discharge (e.g., Chen et al., 2009; Dagg et al., 2004; Tian et al., 1993). Thus, understanding how freshwater discharge influences coastal ecological processes is an important factor in exploring global carbon cycling in the adjacent seas. Under the current conditions of climate change, such heavy freshwater discharge events are predicted to become even more pronounced in the near future because of the dramatic increases in extreme rainfall events and floods predicted to occur throughout the world (Christensen and Christensen, 2003; Knox, 1993; Milly et al., 2002; Palmer and Ralsanen, 2002).

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The East China Sea (ECS) has an approximate area of 0.5 x 10^6 km^2 and is the largest marginal sea in the western Pacific. A tremendous amount of freshwater (956 km^3 yr^{-1}) is discharged annually into the ECS, notably by the Changjiang (a.k.a Yangtze) River, which is the fifth largest river in the world in terms of volume discharge (Liu et al., 2010). On average, the maximum amount of discharge occurs in July, and mean monthly values have ranged from 33,955 to 40,943 m^3 s^{-1} in years of normal weather during the past decade (Gong et al., 2011; Xu and Milliman, 2009). After having been discharged into the ECS, freshwater mixes with seawater to form the Changjiang diluted water (CDW) zone, the salinity (SSS) of which is $\leq$ 31 psu (e.g., Beardsley et al., 1985; Gong et al., 1996). In the CDW, especially in summer, the regional carbon balance is regulated by high rates of plankton community respiration (CR) and PP (Chen et al., 2006; Gong et al., 2003). The rates of CR were also positively associated with the riverine flow rates (Chen et al., 2009). However, few previous studies have shown the effects of floods on biological activity in the ECS (Chung et al., 2014; Gong et al., 2011). Historically, the threshold discharge rates during Changjiang River flooding periods have been estimated to be 4-6 x 10^4 m^3 s^{-1} (Committee, 2001). However, in recent decades, the frequency and magnitude of the Changjiang River flooding events have increased, and this has been attributed to extreme monsoon rainfall associated with climate warming (Jiang et al., 2007; Yu et al., 2009); collectively, these observations suggest that the influence of flooding on the ECS shelf ecosystem

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has intensified. Therefore, it is worthwhile exploring the responses of the biological activities and ecological processes in the ECS to the periodic flooding of the Changjiang River.

In July 2010, a large flood occurred in the Changjiang River (Gong et al., 2011). This event provided an opportunity to understand how flooding affects the ECS shelf ecosystem. Comparative analyses were conducted to examine a number of variables, including physical, chemical, and biological parameters, during a period (July 2009) when the riverine flow was relatively low. The main objective of this study was to reveal the effects of the riverine input of dissolved inorganic nutrients on the plankton communities that support heterotrophic processes in the ECS shelf ecosystem between periods of non-flooding and flooding. To evaluate the differences between these periods, variations in biological variables were compared with CR in order to elucidate their relative importance to CR. In addition, the relationship between CR and the fugacity of CO_2 (fCO_2) was examined to determine the contribution of the plankton communities to variations in fCO_2 in periods of non-flooding and flooding.

MATERIALS AND METHODS

Study area and sampling. This study is part of the Long-term Observation and Research of the East China Sea (LORECS) program. Samples were collected from the ECS in the summers of 2009 (June 29 to July 13) and 2010 (July 6 to 18) during two cruises on the *R/V Ocean Researcher I*. The sample stations were located throughout the ECS shelf (Fig. 1). In July 2010,

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the mean monthly discharge from the Changjiang River reached 60,527 $m^3 s^{-1}$, which was significantly higher than the monthly discharge (33,955 $m^3 s^{-1}$) in the non-flooding year of 2009 (Gong et al., 2011; Yu et al., 2009). Water samples were collected using Teflon-coated Go-Flo bottles (20 L, General Oceanics Inc., USA) mounted on a General Oceanic Rosette® assembly (Model 1015, General Oceanics Inc., USA). At each station, six to nine samples were taken at depths of 3 to 50 m, depending on the depth of the water column. Sub-samples were taken for immediate analyses (dissolved inorganic nutrients, chlorophyll *a* [(Chl *a*)], and bacterial abundance) and on-board incubation of PP and plankton CR. The methods used to collect the hydrographic data and analyze the aforementioned response variables followed Chen et al. (2006; 2013; 2009). Descriptions of the methods used are presented briefly in the following sections. It should also be noted that portions of these results were published by Chung et al. (2014) and Gong et al. (2011).

Physical and chemical hydrographics. Temperature, salinity, and transparency were recorded throughout the water column using a SeaBird CTD (USA). Photosynthetically active radiation (PAR) was measured throughout the water column using an irradiance sensor (4π; QSP-200L). The depth of the euphotic zone (Z_E) was taken as the penetration depth of 1% of surface light. The mixed layer depth (M_D) was based on the potential density criterion of 0.125 units (Levitus, 1982).

A custom-made flow-injection analyzer was used for dissolved inorganic nutrient (e.g., nitrate, phosphate, and silicate) analysis (Gong et al., 2003). Integrated values for the nitrates and other variables in the water column above the Z_E were estimated using the trapezoidal method, in which depth-weighted means are computed from vertical profiles and then multiplied by Z_E (e.g., Smith and Kemp, 1995). The average nitrate concentration over Z_E was estimated from the vertically integrated value divided by Z_E. This calculation was adopted to determine the values of the other variables.

The fugacity of CO_2 (fCO_2) in the surface waters was calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA) data using a program designed by Lewis and Wallace (1998). For details of the TA and DIC measurements, please see Chou et al. (2007).

Biological variables. The water samples taken for Chl *a* analysis were immediately filtered through GF/F filter paper (Whatman, 47 mm) and stored in liquid nitrogen. The Chl *a* retained on the GF/F filters was quantified fluorometrically (Turner Design 10-AU-005; Parsons et al., 1984). When applicable, Chl *a* was converted to carbon units using C:Chl values of 52.9, estimated from shelf waters of the ECS (Chang et al., 2003). To estimate total content of Chl *a* over Z_E integrated for the ECS and the CDW (please see below for details.), Surfer 11 (Golden Software, Inc.) was used. This estimation was also adopted to determine the values for heterotrophic bacteria and zooplankton.

Heterotrophic bacteria samples were fixed in paraformaldehyde at a final concentration of 0.2% (w/v) in the dark for 15 min. They were then immediately frozen in liquid nitrogen and kept at -80°C prior to analysis. The heterotrophic bacteria were stained with the nucleic acid-specific dye SYBR® Green I (emission = 530 ± 30 nm) at a final concentration of 10^{-4} dilution of a commercial solution (Molecular Probes Inc., Oregon, USA) (Liu et al., 2002). They were then identified and enumerated using a flow cytometeter (FACSAria, Becton-Dickinson Co., New Jersey, USA). Known numbers of fluorescent beads (TruCOUNT Tubes, Becton-Dickinson) were simultaneously used to calculate the original cell abundance in each sample. Bacterial abundance was converted to carbon units using a conversion factor of 20 x 10^{-15} g C $cell^{-1}$ (Hobbie et al., 1977; Lee and Fuhrman, 1987).

Zooplankton samples were collected across the whole water column at selected stations using a 330-µm mesh net with a 160-cm diameter opening. Zooplankton samples were digitized to extract the size information (i.e., body width and length) using the ZooScan integrated system, and the size information was used to calculate the ellipsoidal bio-volume of zooplankton (Garcia-Comas, 2010). The biomass (carbon units) of zooplankton was then calculated using the estimated bio-volume following equations of Alcaraz et al. (2003). To estimate the biomass over Z_E, the total biomass of zooplankton over the whole water column was multiple by the fraction of "Z_E relative to depth of the water column" at all stations.

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Primary production (PP) was measured by the ^{14}C assimilation method. The samples were collected and incubated from three depths within the Z_E at stations surveyed during the daylight hours (Gong et al., 2003; Parsons et al., 1984). The samples were pre-screened through a 200-μm woven mesh (Spectrum) and inoculated with $H^{14}CO_3^-$ (final conc. 10 μCi ml^{-1}) in clean 250-ml polycarbonate bottles (Nalgene). The samples were incubated onboard for 2 hrs in chambers filled with running surface seawater and illuminated by halogen bulbs with a light intensity corresponding to the *in situ* irradiance levels (Gong et al., 1999). Following each incubation, the samples were filtered on GF/F filters (Whatman, 25 mm), acidified with 0.5 ml 2 N HCl, and then left overnight. After immersion in 10 ml of a scintillation cocktail (Ultima Gold, Packard), the total activity on the filter was counted using a liquid scintillation counter (Packard 1600). Please note that PP was measured only at selected stations in 2010, but not in 2009.

The plankton community respiration (CR) was measured as the decrease in dissolved oxygen (O_2) during dark incubation (Gaarder and Grann, 1927). CR was measured in samples collected from most stations, with two initial and two dark treatment samples taken from 4-6 depths (depth intervals of 3, 5, 10, 15, 20, and/or 25 m depending on the depth of the water column) within the Z_E at each station. The treatment samples were siphoned into 350-mL biological oxygen demand (BOD) bottles and incubated for 24 hrs in a dark chamber filled with running surface water. Maximum temperature changes were 1.33 ± 0.81 and 2.70 ± 1.43℃ (mean

± SD) during each incubation in 2009 and 2010, respectively. The concentration of O_2 was measured by a direct spectrophotometry method (Pai et al., 1993). The precision of this method was calculated as the root-mean square of the difference between the duplicate samples and was found to be 0.02 and 0.03 mg L^{-1} in 2009 and 2010, respectively. The precision for initial samples in both periods was < 0.01 mg L^{-1}. The difference in O_2 concentration between the initial and the dark treatment was used to compute the CR. A respiration quotient of 1 was assumed in order to convert the respiration from oxygen units to carbon units (Hopkinson Jr., 1985; Parsons et al., 1984).

RESULTS and DISCUSSION

Comparison of hydrographic patterns between flooding and non-flooding periods

In July 2010, the Changjiang River flooded to a devastating extent, and this flood started in late May or early June. The mean monthly water discharge was 60,527 $m^3\ s^{-1}$, and the threshold discharge rate was 4-6 x 10^4 $m^3\ s^{-1}$, making it the largest recorded flooding of the Changjiang River over the last decade (http://yu-zhu.vicp.net/). This rate was almost two times larger than that recorded in the non-flooding period in July 2009 (33,955 $m^3\ s^{-1}$) (Gong et al., 2011; Yu et al., 2009). During the flood, a tremendous amount of freshwater was delivered into the ECS, and the low salinity of the sea surface (SSS ≤ 31 psu) covered almost two thirds of the continental shelf (Fig. 1b). The SSS in the ECS during the 2010 flood was significantly lower than that during the

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2009 non-flooding survey period; the mean (± SD for this and all parameters discussed henceforth) values were 30.32 (± 3.60) and 32.62 (± 2.07) psu, respectively (Table 1). During periods of high discharge from the river, particularly during the summer, the CDW zone is generally distributed within the 60-m isobath region between the latitudes of 27 and 32 °N along the coast (e.g., Beardsley et al., 1985; Gong et al., 1996). During the 2010 flood, the CDW dispersed towards the east and south and reached as far as the 100-m isobath (Fig. 1b). The substantial quantity of freshwater discharged into the ECS could also be seen in the coverage area of the CDW (e.g., Gong et al., 2011); in the 2010 flood, the CDW area (111.7 x 10^3 km^2), approximately six times larger than in the 2009 non-flooding period (19.0 x 10^3 km^2).

Although the mean SSS differed significantly between the flooding and non-flooding periods, there was no difference in the temperature of the sea surface (SST; Table 1). The mean values of SST in 2009 (26.8 ± 1.7) and 2010 (and 26.1 ± 2.2 ℃) were within the range of the mean SST of the ECS in summer (Chen et al., 2009). The mixed layer depth (M_D) did not significantly vary between survey periods: 13.7 (± 7.3) m in 2009 and 11.3 (± 6.6) m in 2010 (Table 1). However, the average M_D was shallower than previously documented values, which ranged from 16.8 to 28.2 m in the ECS during summer (Chen et al., 2009). Even though the mean values of the euphotic depth (Z_E) were slightly deeper in 2009 (38.9±36.4 m) than in 2010 (33.4±17.3 m), there was no statistically significant difference between these depths (Table 1).

Regarding the M_D, the average Z_E in the ECS was also shallower than in a previous study conducted during the summer (Chen et al., 2009). The shallower Z_E could also been indirectly influenced by the transparency of the seawater. The average transparency in summer in the ECS over the past six years (2003-2008) was 81.9% (C.C. Chen, unpublished data). The average transparency values of the ECS in 2009 and 2010 were 76.7% and 80.5%, respectively (Table 1). The averaged values for the CDW zone were relatively low in 2009 (70.0%) and relatively high in 2010 (78.4%) compared to that of the trailing 6-year average (72.7%; C.C. Chen, unpublished data). This might also explain why Z_E in the CDW in 2009 was only 16.8 m (Table 1).

These findings suggest that the growth of phytoplankton might be limited by the availability of light, especially in the CDW zone in 2009. Generally, the transparency of the coastal ocean might be low during flooding periods due to riverine discharge of terrestrial matter. A low transparency value was documented in June 2003 in the ECS, during which the CDW area was 43.1 x10^3 km^2 (Chen et al., 2009), and the average values for the ECS and the CDW were 70.9% and 66.0%, respectively (C.C. Chen, unpublished data). Surprisingly, as stated above, the average transparency in the ECS during the 2010 flood was similar to the value observed over the past six years, and its value (78.4%) in the CDW in 2010 was even higher than that of the trailing 6-year average (72.7%). This could be partially explained by the fact that most large particulates from terrestrial sources might have been confined to and precipitated in the coastal region, not in the expanded CDW region (e.g., Chung et al., 2012). Furthermore, it should also be noted that the sampling period of 2010, even at the peak of the flood, was almost one month after the beginning of this flood. Therefore, it is reasonable to speculate that plankton communities were in the late phase of succession in this flood event (please refer to discussion in next section for more details on this matter). The transparency during the 2010 sampling period might, then, have increased due to organic matter (particulate and dissolved) having been uptaken and transferred to higher trophic levels.

In general, an immense quantity of dissolved inorganic nutrients is delivered from the Chinese coast into the ECS during the wet season, from May to September (Chen et al., 2013; Chen et al., 2009; Gong et al., 1996). This study found a higher concentration of nitrates in the ECS during flooding periods, mostly in the fluvial discharge of the Changjiang River. This finding was supported by the negative linear relationship between SSS and nitrate concentration in the ECS in 2010 (r^2 = 0.37, p < 0.001, n = 37). During the study period, there was also a negative linear relationship between SSS and silicate concentration (r^2 = 0.60, p < 0.001, n = 37), but not between SSS and phosphate concentration (data not shown). The comparison of the two periods showed that the nitrate concentration in the surface water of the ECS was significantly higher in the 2010 flood than in the 2009 non-flooding period, with mean values of 6.2 (± 9.8) and 2.0 (± 5.3) μM, respectively (Table 1). This finding also applied to the average nitrate values

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over Z_E between both periods (data not shown). During the 2010 flood, the mean nitrate concentration, either in the surface water or averaged over $Z_{E,}$ was higher or comparable to that documented during periods of high riverine discharge in the ECS (Chen et al., 2009; Gong et al., 1996). Surprisingly, in the 2010 flood, nitrate levels reached 37.6 μM in the surface water, and the highest nitrate concentrations were observed within the CDW (Fig. 1d).

As for phosphate concentration, there was no significant difference in values of the surface water observed between the 2009 non-flooding period and the 2010 flood, with mean values of 0.13 (± 0.17) and 0.17 (± 0.30) μM, respectively (Table 1). Although mean phosphate values of the surface water in the CDW zone were slightly higher in 2010 (0.23 μM) than in 2009 (0.13 μM), this difference was not statistically significant (Table 1). However, it should be noted that there was one station with extremely high phosphate concentration (1.71 μM) in the surface water in the CDW zone during the 2010 flood (Fig. 1f). Even so, in this period, the mean molar ratio of nitrate to phosphate (N/P) was 22.3 ± 20.9. The high N/P molar ratio was even more pronounced in the CDW, where it was higher than 16 at 14 of the 20 stations, with a mean value of 40.4 (± 22.6). This value was comparable to that of the CDW during high riverine flow periods in the ECS in summer (Chen et al., 2006). During the non-flooding period, the N/P molar ratio was lower than 16, with a mean value of 11.5 (± 20.8).

It has been suggested that phytoplankton growth might be regulated by the availability and/or the N/P ratio of nutrients in the ECS (Gong et al., 1996; Harrison et al., 1990). The results of this study indicate that in the 2009 non-flooding period, phytoplankton biomass might have been regulated by the availability of dissolved inorganic nitrogen to a greater extent than it was during the 2010 flood. However, in the 2010 flood, phytoplankton growth was likely limited by phosphates. Phytoplankton growth limited by different inorganic nutrients in varying periods has been observed in estuaries and coastal regions, such as Chesapeake Bay in the United States (Fisher et al., 1992; Harding, 1994). In the ECS, phosphates have been frequently found as a factor limiting phytoplankton growth, especially in the CDW (Chen et al., 2004; Gong et al., 1996; Harrison et al., 1990).

Plankton activities associated with the Changjiang River flood

Following the discharge of fluvial nutrients into the ECS, phytoplankton are generally abundant in the CDW region. The Chl *a* concentration in the CDW even reached bloom criteria (> 20 mg Chl m^{-3}) in past years in the ECS (Chen et al., 2009; Chen et al., 2003). Surprisingly, the phytoplankton biomass was not as high as expected in this study, even though a high nitrate concentration was observed during the 2010 flood. The mean values of Chl *a* in the surface water of the ECS in 2009 and 2010 were 0.98 (± 1.52) and 1.26 (± 1.27) mg Chl m^{-3}, respectively (Table 1). However, these mean values were still at the high end of the Chl *a* concentration range normally documented in the ECS in the mid-summer through July/August period (Chen et al.,

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2009). In both periods, the phytoplankton biomass in the surface water was generally higher in the CDW than in other regions of the ECS (Fig. 1g and h). For example, in the 2010 flood, the maximum Chl *a* value reached 5.32 mg Chl m^{-3} in the CDW (Table 1; Fig. 1h). In the 2010 flood, the Chl *a* values were positively related to nitrate and silicate concentrations (all $p < 0.001$), but not phosphate concentrations ($p = 0.09$), in the surface water. The linear relationship between Chl *a* and phosphate values in the surface water, however, became significance ($p < 0.001$) if one outlier with a markedly high phosphate concentration (1.71 μM) was excluded from this analysis (Fig. 1f). In the 2009 non-flooding period, the Chl *a* concentration was significantly, positively, and linearly associated with concentrations of all measured nutrients: nitrate, silicate, and phosphate ($p < 0.01$ in all cases).

The spatial distribution pattern of Chl *a* documented in this study was similar to that found in previous studies of the ECS (Gao and Song, 2005; Gong et al., 2011). However, it should be noted that the CDW zone was extensive during the 2010 flood. Nevertheless, the phytoplankton biomass in the surface water (Table 1), or averaged over Z_E (data not shown), did not differ significantly between 2009 and 2010. An effect of flooding on phytoplankton biomass was, however, observed if using total content of Chl *a* over Z_E integrated for the entire ECS or the CDW zone. The total Chl *a* content in the ECS was higher in 2010 than in 2009, with values of 5.5 and 4.4 x 10^6 kg Chl *a*, respectively (Table 2). The Chl *a* content in the CDW zone was even

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higher in 2010 than in 2009, with values of 3.9 and 1.2 x 10^6 kg Chl *a*, respectively (Table 2). In the 2010 flood, PP in the surface water was high, with a mean (± SD) value of 62.1 (±33.8) mg C m^{-3} d^{-1} (Table 1). This value was comparable to the high PP values documented in the ECS in summer in prior works (Chen et al., 2009). In contrast, the PP:Chl *a* value was higher in the 2010 flood compared to that documented by Chen et al. (2009), with mean values of 27.1 (±17.2) and 19.7 (±5.5) mg C mg Chl^{-1} d^{-1}, respectively.

Gong et al. (2011) estimated that over the past decade, the average rate of carbon fixation during flooding periods was about three times higher than during non-flooding periods. During the 2010 flood, the rate reached 176.0 x 10^3 tons C d^{-1} in the CDW (Gong et al., 2011). Gong et al. (2011) also showed that the abundance of phytoplankton was twice as high in the CDW than in the other regions. In the 2010 flood, the phytoplankton communities predominantly consisted of diatoms, especially *Chaetoceros* spp., *Rhizosolenia* spp., and *Nitzschia* spp. (Gong et al., 2011). However, the phytoplankton assemblage was not measured in 2009. In July 2007, when the amount of freshwater discharge was similar to that of 2009 (Gong et al., 2011), the phytoplankton in the CDW were predominantly diatoms and other algal taxa, including dinoflagellates, coccolithophorids, and green algae (Chien, 2009). Picocyanobacteria, particularly the phycocyanin-rich *Synechococcus*, were predominant in the CDW, and they showed similar spatial distribution patterns in both 2009 and 2010 (Chung et al., 2014). In addition, the phycoerythrin-rich *Synechococcus* covered most of the ECS continental shelf, but they were less abundant in 2010 than in 2009 (Chung et al., 2014). Furthermore, the decreased presence of *Prochlorococcus* was also observed in regions other than the CDW in both periods (Chung et al., 2014). These results imply that the phytoplankton community assemblage might have differed between the flooding and non-flooding periods investigated in this study, even though the phytoplankton biomass did not vary significantly between them.

In summer, heterotrophic bacterioplankton are generally more abundant in the CDW of the ECS than in other regions (Chen et al., 2006; Chen et al., 2009). Chen et al. (2006) suggested that the growth of bacteria along the coast might be stimulated by the substantial amount of organic matter derived from both autochthonous marine production and fluvial runoff. This spatial distribution pattern was also observed in 2009 and 2010. In the 2009 non-flooding period, the mean values of the bacterial biomass in the surface water of the CDW and all other areas were 77.5 (± 55.7) and 31.0 (± 18.6) mg C m^{-3}, respectively. Their mean values in the 2010 flood were 24.4 (± 18.6) and 15.0 (± 11.5) mg C m^{-3} in the CDW and other regions, respectively. Further analyses revealed that the bacterial biomass in the surface water was positively and linearly associated with Chl *a* concentrations in both 2009 ($p < 0.01$) and 2010 ($p < 0.05$). This finding applies to the values averaged over Z_E in both periods (both $p < 0.01$). These results suggest that in both study periods, bacterial growth might have been associated with the organic carbon derived from phytoplankton. However, the mean values of Chl *a* concentrations in the surface water were slightly higher in 2010 than in 2009 (Table 1).

In general, an increased amount of organic matter is delivered through fluvial discharge into the ECS during periods of high riverine flow (e.g., Wang et al., 2012). Although these results suggest that the bacterial biomass might be higher in the flooding period than in the non-flooding period, this difference was not verified when using averaged bacterial biomass values in this study. The bacterial biomass in the surface water was significantly higher in the 2009 non-flooding period than during the 2010 flood, with mean values of 39.8 (± 33.7) and 20.4 (± 16.5) mg C m^{-3}, respectively (Table 1). The average bacterial value over Z_E was even more pronounced in 2009 than in 2010 (data not shown). However, the total bacterial biomass in the CDW zone was two times higher in 2010 than in 2009, with values of 47.7 and 21.0 x 10^6 kg C, respectively (Table 2).

In addition, the major taxa of bacterioplankton varied between both periods (C.C. Chung, unpublished data). During the non-flooding period, cyanobacteria were predominant (70% of the bacterioplankton community) at the selected sampling stations located either in the CDW zone or in other regions of the ECS. During the 2010 flood, such a high percentage of cyanobacteria was observed only at stations located in regions other than the CDW. At this survey time, in addition to cyanobacteria, the dominant taxa of bacterioplankton in the CDW zone also included

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favobacteria, gammabacteria, alphabacteria, and actinobacteria. A potential cause of the low average bacterial biomass observed during the 2010 flood might be protozoan grazing. Protozoa have been recognized as important microbial grazers in the ECS and in many coastal ecosystems (e.g., Chen et al., 2009; Chen et al., 2003; Sherr and Sherr, 1984). Although protozoan abundance was not measured in this study, a high production rate of nanoflagellates was observed in the southern ECS, with mean values of 0.46 μg C l^{-1} h^{-1} during periods of high riverine flow (Tsai et al., 2005).

Zooplankton are amongst the most important contributors to plankton CR (Calbet and Landry, 2004; Hernández-León and Ikeda, 2005; Hopkinson Jr. et al., 1989). In this study, zooplankton were only sampled across the whole water column. However, the average biomass of zooplankton over Z_E can be still estimated. The zooplankton biomass over Z_E was significantly higher in the 2010 flood than in the 2009 non-flooding period, with mean values of 105.7 (± 144.4) and 22.6 (± 25.7) mg C m^{-3}, respectively ($p < 0.01$). The average zooplankton biomass over Z_E for the CDW zone was 90-fold higher in 2010 than in 2009 (Table 2), suggesting that the flood may have had a significant effect on zooplankton biomass. The high zooplankton biomass observed in 2010 also implies that plankton communities might be in the late phase of succession during this flood event.

Effects of the Changjiang River flooding on plankton community respiration

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Plankton CR has been assumed to be an integrated rate of organic carbon consumption by plankton communities (e.g.., Hopkinson Jr. et al., 1989; Rowe et al., 1986). In summer, the mean CR rate in the surface water of the ECS ranges from 52.2 to 128.4 mg C m^{-3} d^{-1} (Chen et al., 2006; Chen et al., 2009). The CR rate has been significantly correlated with fluvial discharge from the Changjiang River (Chen et al., 2009). In this study, the CR in the surface water ranged from 2.7 to 311.9 mg C m^{-3} d^{-1}, with a mean value of 73.2 (± 76.9) mg C m^{-3} d^{-1} in the 2009 non-flooding period (Table 1). During the 2010 flood, this rate in the surface water was significantly higher than in 2009 ($p < 0.01$; Table 1). The value of CR in the surface water was in the range of 10.9-325.3 mg C m^{-3} d^{-1}, with a mean value of 105.6 (± 66.7) mg C m^{-3} d^{-1} (Table 1). The CR rate averaged over the Z_E was also higher in 2010 than in 2009, with mean values of 76.8 (±53.0) and 66.8 (±68.4) mg C m^{-3} d^{-1}, respectively. However, the difference was not statistically significant ($p = 0.08$). In terms of spatial distribution, higher CR rates were mostly observed in the CDW region in both sampling periods, especially along the coast (Fig. 2). Nevertheless, it should be noted that the CDW widely expanded in 2010 compared to during 2009. These results also reveal that the CR in the summer of the 2010 flood was at the high end of the values typically observed in the ECS (Chen et al., 2006; Chen et al., 2009), suggesting that the CR might have been enhanced by the Changjiang River flooding in 2010.

To assess the biotic controls on CR, the rates were regressed against biomass of

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phytoplankton, heterotrophic bacteria, and zooplankton, as well as primary production (when applicable). An analysis of the pooled data in each period show that CR was significantly correlated with Chl *a* concentrations and bacterial biomass (both $p < 0.001$; Fig. 3). In both periods, the linear relationship was also statistically significant between CR and Chl *a* concentration and between CR and bacterial biomass, both for the surface water and when averaged over Z_E (all $p < 0.01$). In addition, in the 2010 flood, CR was significantly correlated with PP in the pooled data, surface water, or when averaged over Z_E (all $p \leqq 0.01$). Compared with a previous study in the ECS (Chen et al., 2009), CR (g O_2 m^{-3} d^{-1}) was also scaled as a power function of PP (g O_2 m^{-3} d^{-1}) in the 2010 flood, where CR = 5.78 $PP^{1.24}$ (p = 0.001; Fig. 4). Note that the exponent (1.24) represents the slope of the log-log transformation. This value is larger than previous values reported for the ECS (CR = 0.58 $PP^{0.46}$) and other coastal ecosystems in the world (CR = 1.1 $PP^{0.72}$) (Chen et al., 2009; Duarte and Agustí, 1998). To support higher CR, Chen et al. (2009) suggests that external substrates transported from the river into the ECS might be an important source during the high-flow summer. This finding however suggests that during the 2010 flood, in addition to allochthonous organic matter, the higher CR rate might have also been fueled by *in situ* organic carbon production, such as PP. The important contribution of phytoplankton and/or bacterioplankton to CR has been identified in the ECS, even though its relative contribution might vary spatially or temporally (Chen et al., 2006; Chen et al., 2009;

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Chen et al., 2003). These results suggest that the CR rate might be dominated by phytoplankton and bacterioplankton in the 2009 non-flooding period. During the 2010 flood, the higher CR could be attributed to vigorous plankton metabolic activities, especially phytoplankton.

Surprisingly, the mean Chl *a* value was slightly higher in 2010 than in 2009. In contrast, the bacterial biomass was significantly lower in 2010 than in 2009 (Table 1). However, the CR rate was still higher in 2010 than in 2009. To gain greater insight, the differences (i.e., 2010 minus 2009) in the average CR, Chl *a* concentration, and bacterial biomass over Z_E at the same station between two periods were compared. The extent of such differences in CR was significantly related to differences in Chl *a* concentration ($p < 0.001$) and bacterial biomass ($p < 0.01$; Fig. 5). The linear relationships were also statistically significant if the values of the differences in the surface water were applied (all $p < 0.01$; data not shown). Among the positive CR difference values (i.e., 20 of 33), 15 stations were also characterized by positive differences in Chl *a* concentrations, but only two stations had positive differences in bacterial biomass. Interestingly, the stations with positive Chl *a* concentration difference values were mostly located within the CDW region in 2010, with the exception of the CDW in 2009. These results suggest that the higher CR in the 2010 flood might be attributed to phytoplankton. The mean Chl *a* concentration was only slightly higher in 2010 than in 2009. However, the phytoplankton assemblage varied between periods. Therefore, it is reasonable to speculate that the differences in CR rate in both

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periods might have been partially caused by variation in the composition of the phytoplankton communities. Although the CR attributed to different components of the phytoplankton community was not measured in this study, it was been documented elsewhere (e.g., Lopez-Sandoval et al., 2014).

In addition, zooplankton might also be amongst the potential contributors to the higher CR rate observed in 2010 than in 2009. As stated above, the biomass of zooplankton was significantly higher in 2010 than in 2009. However, the linear relationships between CR and zooplankton biomass over Z_E were not statistically significant in 2009 or 2010. To further explore how plankton communities contributed to CR, the CR rate was regressed against total plankton biomass (i.e., summed biomass of phytoplankton, bacterioplankton, and zooplankton) for both periods. The linear relationships were significant between CR and total plankton biomass (mg C m^{-3}) over Z_E both in 2009 ($p < 0.001$) and 2010 ($p < 0.01$; Fig. 6). Similarly significant relationships between CR and total planktonic biomass have also been observed in the summer in the ECS, and phytoplankton and bacterioplankton might be the most important components contributing to CR at such times (Chen et al., 2006). In this study, autotrophic plankton biomass (i.e., phytoplankton) accounted for 41.3% and 45.6% of total planktonic biomass in 2009 and 2010, respectively. As for heterotrophic plankton biomass, bacterioplankton attributed to 38.7% and 11.3% and zooplankton contributed for 20.0% and 43.1% of total plankton biomass in 2009 and 2010, respectively. This suggests that phytoplankton and bacterioplankton might be the most important components attributing to CR in the 2009 non-flooding period. In contrast, during the 2010 flood, the CR rate might have been mostly driven by phytoplankton and zooplankton metabolic activity. Even though, this conclusion was derived from stocks, and the biomass might not be directly related to the concurrent CR rate. By using physiological and allometric relationships of variant plankton communities, the individual CR rate of plankton could be estimated from its stock and significant regression has been found between measured and estimated rates (Chen et al., 2009). Furthermore, it also should be noted that microzooplankton might be another important contributor to CR. Unfortunately, it was not measured and could not evaluate its contribution to CR in this study.

Implications of community metabolism in the coastal ecosystem

To evaluate the metabolic balance of the plankton community, the P/R ratio of PP to CR can be used as an index (e.g., Duarte and Agustí, 1998; Kemp et al., 1997). It also should be noted that in this study, the P/R ratio might be under-estimated because the values of P (i.e., PP) and R (i.e., CR) were integrated over Z_E instead of over the entire water column. In the 2010 flood, the P/R ratio was in the range of 0.11 to 1.33, but it could not be calculated in 2009 since PP was not measured in this period. Surprisingly, the mean P/R ratio was similar to that in the summer in the ECS, with a mean value of 0.42 ± 0.33 (Chen et al., 2009). This value, however, was much lower

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than the P/R ratio reported in other coastal ecosystems (Duarte and Agustí, 1998). This result implies that a large amount of organic carbon was respired by the plankton community into the water column during the flooding period. In addition to phytoplankton, zooplankton may have also contributed significantly to the high CR in 2010. This assumption is supported by the fact that high zooplankton biomass (mean value = 105.7 mg C m^{-3}) was documented during this period, and zooplankton also accounted for 43.1% of the total plankton biomass. This result also suggests that in the 2010 flood, the ECS shelf ecosystems were net heterotrophic. A heterotrophic ecosystem was documented in the ECS in summer and in other seasons (Chen et al., 2006; Chen et al., 2013; Chen et al., 2003). A low P/R ratio (i.e., < 1) has been widely observed in coastal ecosystems worldwide (e.g., del Giorgio et al., 1997; Duarte and Agustí, 1998).

A further comparative analysis was conducted to determine whether the CR rate affected the fugacity of CO_2 (fCO_2) in the seawater. In 2009, the fCO_2 in the surface water was in the range of 118.7-599.8 μatm, with mean values of 362.9 ± 101.2 μatm (Table 1). This mean value is close to the mean value (369.6 μatm) observed in the ECS in August in prior years (Chen et al., 2006). In the 2010 flood, the mean value (297.6 μatm) of fCO_2 in the surface water was significantly lower than in 2009, and ranged from 178.7 to 454.2 μatm (Table 1). It is well known that fCO_2 is temperature dependent, and it increases as the temperature increases (e.g., Goyet et al., 1993). The effect of temperature on the large variation in fCO_2 observed between the 2009 non-flooding

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period and the 2010 flood might be trivial, though, because the SST was similar in both periods (Table 1).

The effect of freshwater on fCO_2 in the surface water in the ECS has also been suggested to be relatively minor compared to the inter-annual variation of fCO_2 (Chen et al., 2013). To evaluate this, conservative mixing was applied by using TA and DIC data between freshwater and seawater end-members. The TA and DIC data reported by Zhai et al. (2007) for the Changjiang River in summer were used as freshwater data (both TA and DIC = 1743 μmol kg^{-1}). The surface data at Station K, shown at the bottom right-hand side of Fig. 1, were selected to represent the seawater data (SSS = 33.96, TA = 2241 μmol kg^{-1}, and DIC = 1909 μmol kg^{-1} in 2009; SSS = 33.96, TA = 2240 μmol kg^{-1}, and DIC = 1904 μmol kg^{-1} in 2010). The simulated results show that the effect of mixing freshwater and seawater on fCO_2 was nearly the same in both periods. However, a large variation in fCO_2 in the surface water was estimated; it varied from 439.8 to 375.4 μatm within a salinity range of 20.38 to 33.96. This finding implies that surface water fCO_2 in the ECS might increase dramatically, especially during the devastating flood of 2010 where low SSS (≤ 31 psu) characterized almost 70% of the ECS shelf (Fig. 1b).

However, in the 2010 flood, surface water with low fCO_2 was observed in the ECS. Therefore, vigorous photosynthetic processes might be a potential cause for the reduction of fCO_2 in the surface water during periods of flooding. Compared to PP values observed in summer in the ECS in previous years (Chen et al., 2009), primary production was indeed high during the 2010 flood (Table 1; Chen et al., 2009). Gong et al. (2011) also estimated that over the past decade, the carbon fixation rate during flooding was about three times higher than during non-flooding periods. However, no significant relationship was found between fCO_2 and PP in the 2010 flood, though this may simply be due to having a small sample size for PP. Nevertheless, fCO_2 was significantly related to Chl *a* concentration in the pooled data of the 2010 flood ($p < 0.001$). This significant relationship indirectly supports that the reduction in fCO_2 in the 2010 flood might be associated with vigorous phytoplankton metabolic activity. Furthermore, negative linear relationships were observed between fCO_2 and CR in the surface water during both the 2009 non-flooding period ($p < 0.01$) and in the 2010 flood ($p < 0.001$; Fig. 7). Significant linear relationships were also found using pooled data from each period (all $p < 0.001$). CR has been assumed to be an integrated response of overall plankton activity. These results imply that fCO_2 in the surface water (or water column) is related to plankton activities. To explore the variations in fCO_2 between the non-flooding and flooding periods, the difference in fCO_2 and CR at the same station was estimated. Surprisingly, a negative linear relationship was found between the difference in fCO_2 and CR of the flooding and non-flooding periods ($p = 0.001$; Fig. 8). As previously stated, compared to the 2009 non-flooding period, the increase in CR rate in the 2010 flood might be associated with the increase in phytoplankton biomass (Fig. 5a). These results indicate that the significant amount of fCO_2 absorption in the 2010 flood was related to the strength of plankton activity, particularly phytoplankton at stations that were not characterized by low SSS in the 2009 non-flooding period.

CONCLUSION

Riverine run-off has a profound effect on organic carbon production and consumption in coastal ecosystems globally. It has become even more pronounced with the dramatic increase in extreme rainfall events and flood magnitude in the Changjiang River and around the world. In July 2010, a devastating flood occurred in the Changjiang River, and this flood started in late May or early June. This event provided an opportunity to investigate the effects of flooding on pelagic ecosystem and plankton community respiration (CR) in the ECS shelf. A comparative analysis was conducted between the data obtained during this flood versus those gathered in July 2009, when the riverine flow was relatively low. During the flood, a large amount of freshwater was discharged into the ECS. The CDW zone, where SSS $\leq$ 31 psu, covered almost two thirds of the continental shelf. In the 2010 flood, the CDW zone was approximately six times larger than in the 2009 non-flooding period.

Higher nitrate concentrations, mostly in the fluvial discharge of the Changjiang River, were also measured in the ECS during the flood. The comparison of both periods showed that the nitrate concentration in the surface water of the ECS was significantly higher in the 2010 flood

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than in the 2009 non-flooding period. Nevertheless, the phytoplankton biomass in the surface water or averaged over the Z_E showed no significant difference between 2009 and 2010. An effect of flooding on phytoplankton biomass was still observed when using total Chl *a* content over Z_E integrated for the entire ECS or the CDW zone, and the total Chl *a* content in the ECS was higher in 2010 than in 2009. In addition, in the 2010 flood, PP in the surface water was relatively high when compared to PP observed in prior works. Gong et al. (2011) estimated that the average rate of carbon fixation during the flood was 176.0 x 10^3 tons C d^{-1}, which was about three times higher than during non-flooding periods over the past decade.

Phytoplankton abundance was twice as high in the CDW than in other regions. In the 2010 flood, the phytoplankton communities predominantly consisted of diatoms; this is in contrast to assemblages documented during non-flooding periods, in which dinoflagellates, coccolithophorids, and green algae were also common (Chien, 2009). Surprisingly, the bacterial biomass in the surface water was significantly higher in the 2009 non-flooding period than in the 2010 flood. Despite this, CR was still higher during the 2010 flood than in the 2009 non-flooding period, with mean ± SD values of 105.6 ± 66.7 and 73.2 ± 76.9 mg C m^{-3} d^{-1} in the surface water, respectively. The 2010 flood minus the 2009 non-flooding period difference in CR was significantly related to the respective differences in Chl *a* concentration, suggesting that higher CR in the 2010 flood might have been attributed to a higher biomass of phytoplankton, especially in stations located within the CDW region (most of which were not characterized by low SSS in the 2009 non-flooding period). In addition to phytoplankton, zooplankton might be another important component contributing to the high CR rate observed in the 2010 flood. This could be evidenced from the fact that zooplankton biomass in 2010 accounted for 43.1% of the total plankton biomass (i.e., summed biomass of phytoplankton, bacterioplankton, and zooplankton).

Finally, a negative linear relationship was found between the differences (i.e., 2010 minus 2009) in CR vs. fCO_2. This finding implies that a tremendous amount of fCO_2 was absorbed by vigorous photosynthetic activity during the flood period. Overall, these results suggest that plankton activity flourished in the substantial amount of dissolved inorganic nutrients discharged by the river during the flood. This effect was especially pronounced at stations not previously characterized by low SSS, indicating that the effects of flooding on the ECS shelf ecosystem might be scaled to the magnitude of the flood.

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Table 1. Range of values for different variables in the surface water of the ECS during non-flooding (2009) and flood (2010) periods, with mean ± SD in parentheses and in brackets for all sampling stations and for stations in the area of the Changjiang Diluted Water (CDW) region, respectively. Variables include transparency (CTD_{TM}; %), salinity (SSS; psu), temperature (SST; ℃), fugacity of CO_2 (fCO_2; μatm), nitrate (NO_3^-; μM), phosphate (PO_4^{3-}; μM), silicate (SiO_4^-; μM), chlorophyll *a* (Chl *a*; mg Chl m^{-3}), bacterial biomass (BB; mg C m^{-3}), primary production (PP; mg C m^{-3} d^{-1}), and plankton community respiration (CR; mg C m^{-3} d^{-1}). For reference, values of euphotic depth (Z_E; m) and mixed layer depth (M_D; m) are also shown. The Mann-Whitney Rank Sum test was applied for variable comparisons between 2009 and 2010, and the results are indicated as described in the table footnotes.

Variable	2009	2010
Z_E	1.3–190.6 (38.9±36.4) [16.8±7.4]	10.1–82.2 (33.4±17.3) [24.8±10.7]
M_D	5–37 (13.7±7.3) [7.3±3.6]	4–35 (11.3±6.6) [7.9±2.6]
CTD_{TM}	37.2–86.3 (76.7±12.2) [70.0±4.9]	67.7–88.5 (80.5±5.4) [78.4±4.3]**
SSS	23.80–34.11 (32.62±2.07) [29.24±2.52]	19.33–34.27 (30.32±3.60)* [27.95±3.03]
SST	23.3–29.6 (26.8±1.7) [25.0±0.9]	21.0–30.0 (26.1±2.2) [25.1±1.7]
fCO_2	118.7–599.8 (362.9±101.2) [230.4±105.3]	178.7–454.2 (297.6±79.0)* [248.6±54.5]
NO_3^-	0.0–24.3 (2.0±5.3) [4.0±9.1]	0.0–37.6 (6.2±9.8)* [10.3±11.3]*
PO_4^{3-}	0.00–0.83 (0.13±0.17) [0.13±0.07]	0.00–1.71 (0.17±0.30) [0.23±0.37]

SiO_4^-	1.5–24.5 (5.8±5.9) [9.8±7.2]	0.6–36.4 (6.4±7.8) [9.1±9.2]
Chl *a*	0.12–4.41 (0.98±1.52) [2.23±1.46]	0.03–5.32 (1.26±1.27) [1.83±1.35]
BB	10.6–184.8 (39.8±33.7) [54.9±39.6]	3.6–90.2 (20.4±16.5)** [24.4±18.6]**
PP	– –	10.0–111.3 (62.1±33.8) [71.0±29.1]
CR	2.7–311.9 (73.2±76.9) [172.0±109.2]	10.9–325.3 (105.6±66.7)* [142.0±61.2]

–: no data; *: $p < 0.01$; **: $p < 0.001$

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Table 2. Total biomass of biological variables over the euphotic depth integrated for the whole ECS and the Changjiang Diluted Water region (in parentheses) during non-flooding (2009) and flooding (2010) periods. Variables include chlorophyll *a* (Chl *a*; x 10^6 kg Chl), bacterial biomass (BB; x 10^6 kg C), and zooplankton (Zoo; x 10^6 kg C). For reference, the areas (x 10^3 km^2) of the entire ECS and CDW regions are also shown.

Variables	2009 (non-flooding period)	2010 (flood)
Area	186.0 (19.0)	182.7 (111.7)
Chl *a*	4.4 (1.2)	5.5 (3.9)
BB	222.5 (21.0)	87.3 (47.7)
Zoo	410.3 (6.2)	920.6 (560.8)

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FIGURE LEGENDS

Fig. 1. Contour plots of salinity (SSS), nitrate (NO_3^-), phosphate (PO_4^{3-}), and chlorophyll *a* (Chl *a*) in the surface water (2-3 m) in the ECS during non-flooding (2009; left most panels) and flooding (2010; right-most panels) periods. Bottom depth contours are shown as dashed lines, both here and in Fig. 2. The sampling stations in both periods are marked by an ex (x), both here and in Fig. 2. The contour intervals of SSS, nitrate, phosphate, and Chl *a* are 0.5 psu, 1.0 µM, 0.1 µM, and 0.5 mg Chl m^{-3}, respectively. For reference, the contour lines (bold) of SSS = 31 psu, NO_3^- = 3.0 µM, PO_4^{3-} = 1.0 µM, and Chl *a* = 1.0 mg Chl m^{-3}. The range for each parameter is shown at the top of each panel.

Fig. 2. Contour plots of plankton community respiration (CR; mg C m^{-3} d^{-1}) over the euphotic zone of the ECS during a) non-flooding (2009) and b) flooding (2010) periods. The contour interval is 10 mg C m^{-3} d^{-1}. The CR range is shown at the top of each panel.

Fig. 3. Relationships between plankton community respiration (CR; mg C m^{-3} d^{-1}) and a) chlorophyll *a* concentration (Chl *a*; mg Chl m^{-3}) and b) bacterial biomass (mg C m^{-3}) for all data from non-flooding (2009; ●) and flooding (2010; ○) periods. Linear regressions of data from 2009 (solid lines) and 2010 (dashed lines), as well as the respective r^2 and p values, have also been included.

Fig. 4. Log-log relationships between averaged volumetric rates of primary production (PP, converted to O_2 units) and volumetric rates of CR in 2010 (●). Please note the log scale of both axes. The solid line shows the relationship as a power function of PP. For comparison, the estimated power function of CR versus PP (CR = 0.58 $PP^{0.46}$) in summer (○) in the ECS is shown as a dashed gray line (Chen et al., 2009).

Fig. 5. Differences (Δ) between 2010 and 2009 in plankton community respiration (CR; mg C m^{-3} d^{-1}) versus a) chlorophyll *a* (Chl *a*; mg Chl m^{-3}) and b) bacterial biomass (mg C m^{-3}) over

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the euphotic zone at the same station. The r^2 and p values have been shown for the best-fit linear regression line (solid line). For reference, the vertical and horizontal dashed lines represent inter-year differences of zero (i.e., $\Delta = 0$).

Fig. 6. Relationship between plankton community respiration (CR) and total plankton biomass (expressed per carbon unit) over Z_E in 2009 (●; solid line) and 2010 (○; dashed line). The respective p and r^2 values are shown for each linear regression line. Total plankton biomass was the summed biomass of phytoplankton, bacterioplankton, and zooplankton. Please refer to the "Materials and Methods" for details of the carbon conversion for plankton communities.

Fig. 7. Relationships between the fugacity of CO_2 (fCO_2) and plankton community respiration (CR) in the surface water in 2009 (●; solid line) and 2010 (○; dashed line). The respective p and r^2 values are shown for each linear regression line.

Fig. 8. Differences (Δ) between 2010 and 2009 in fCO_2 (μatm) and plankton community respiration (CR; mg C m^{-3} d^{-1}) in the surface water at the same station. For reference, the vertical and horizontal dashed lines represent the inter-annual differences of zero (i.e., $\Delta = 0$).

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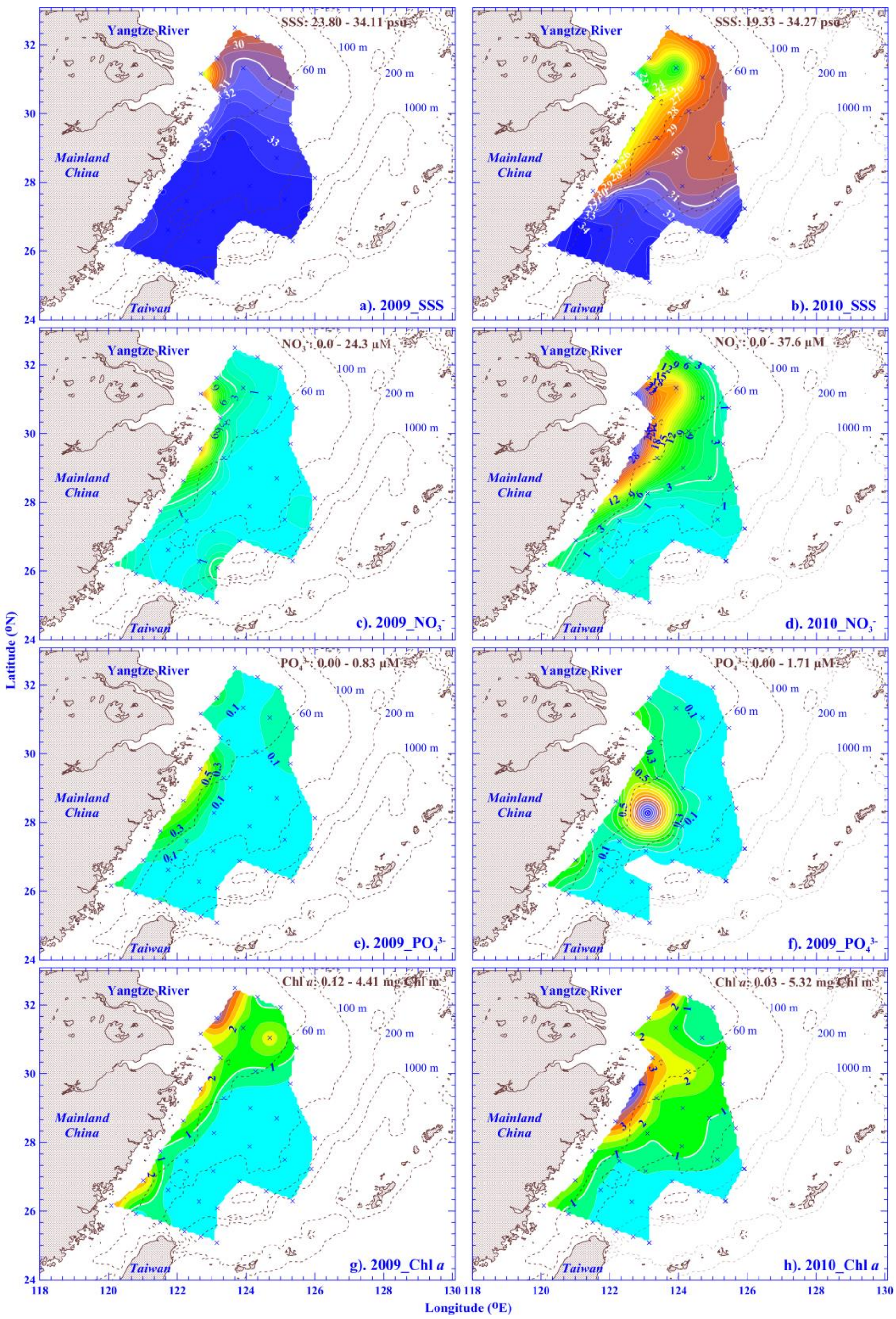

Fig. 1

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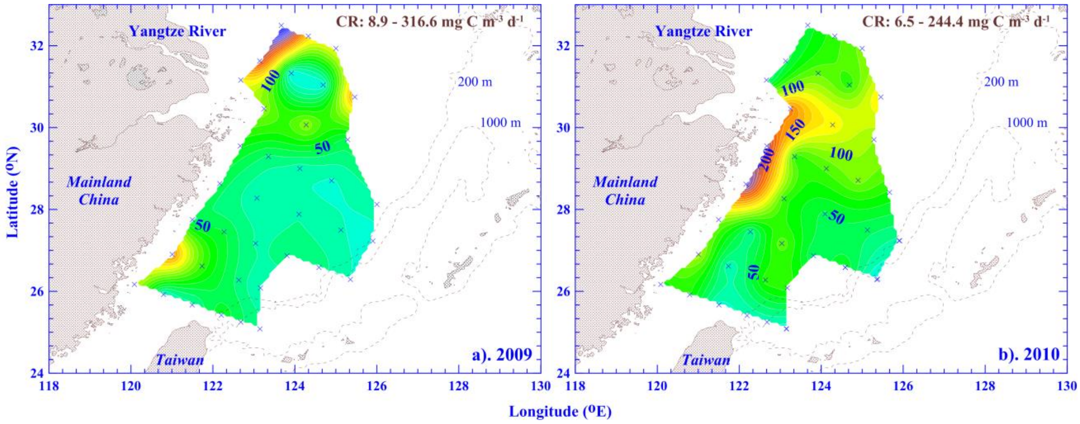

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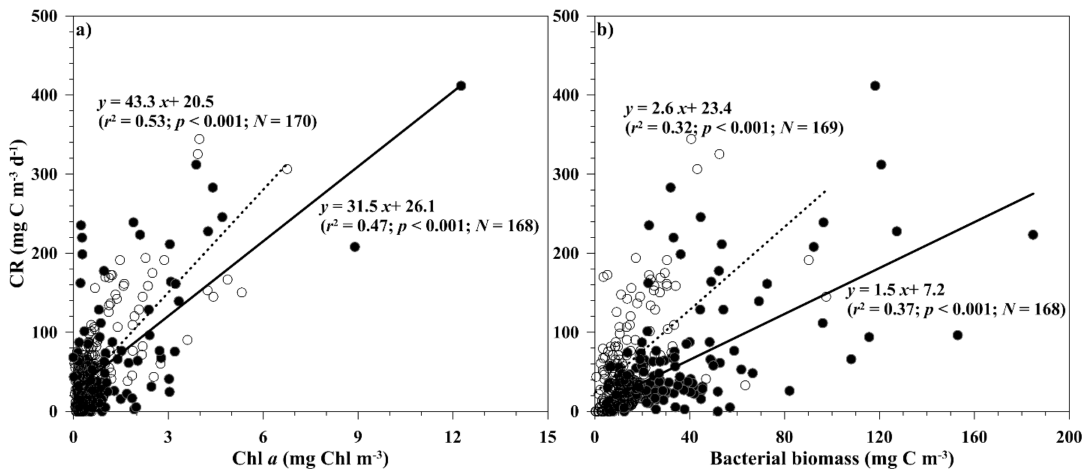

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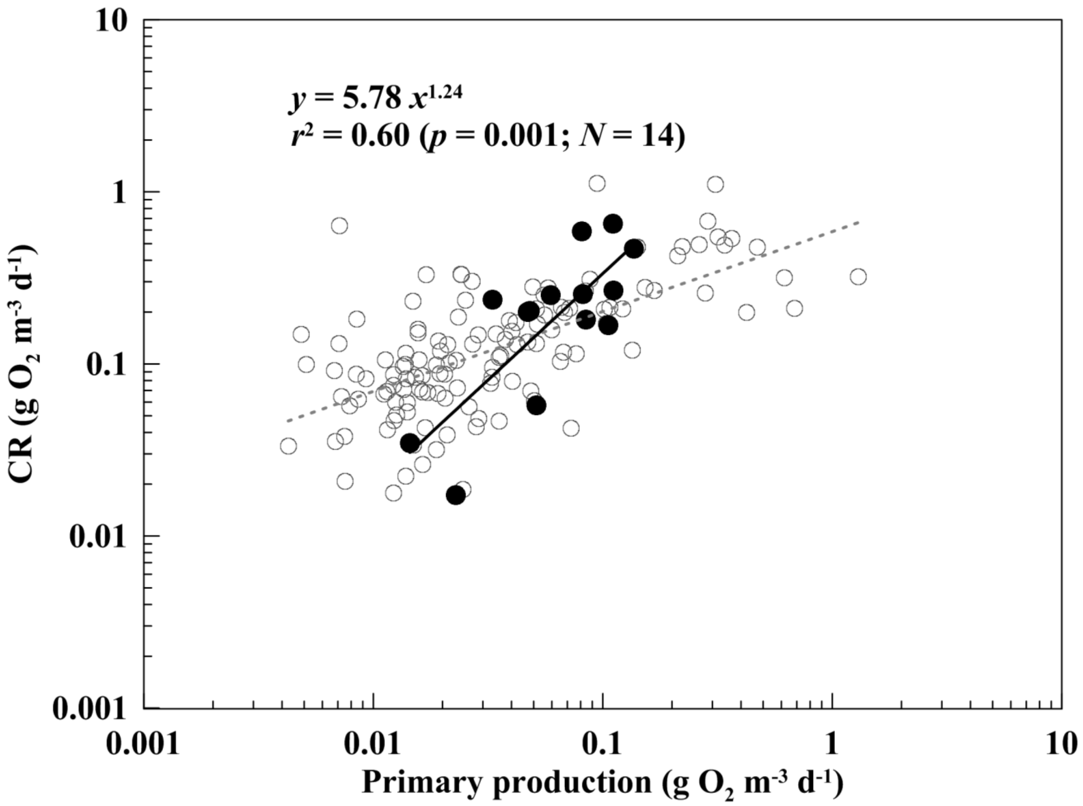

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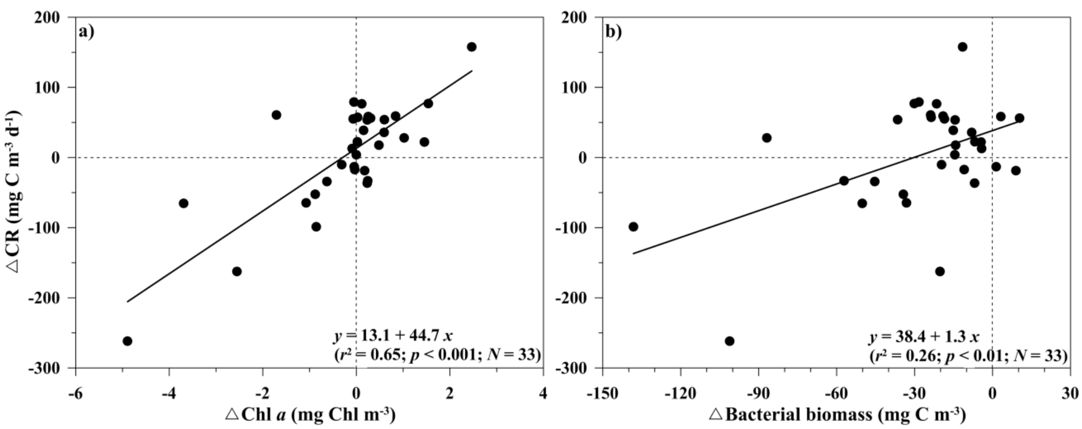

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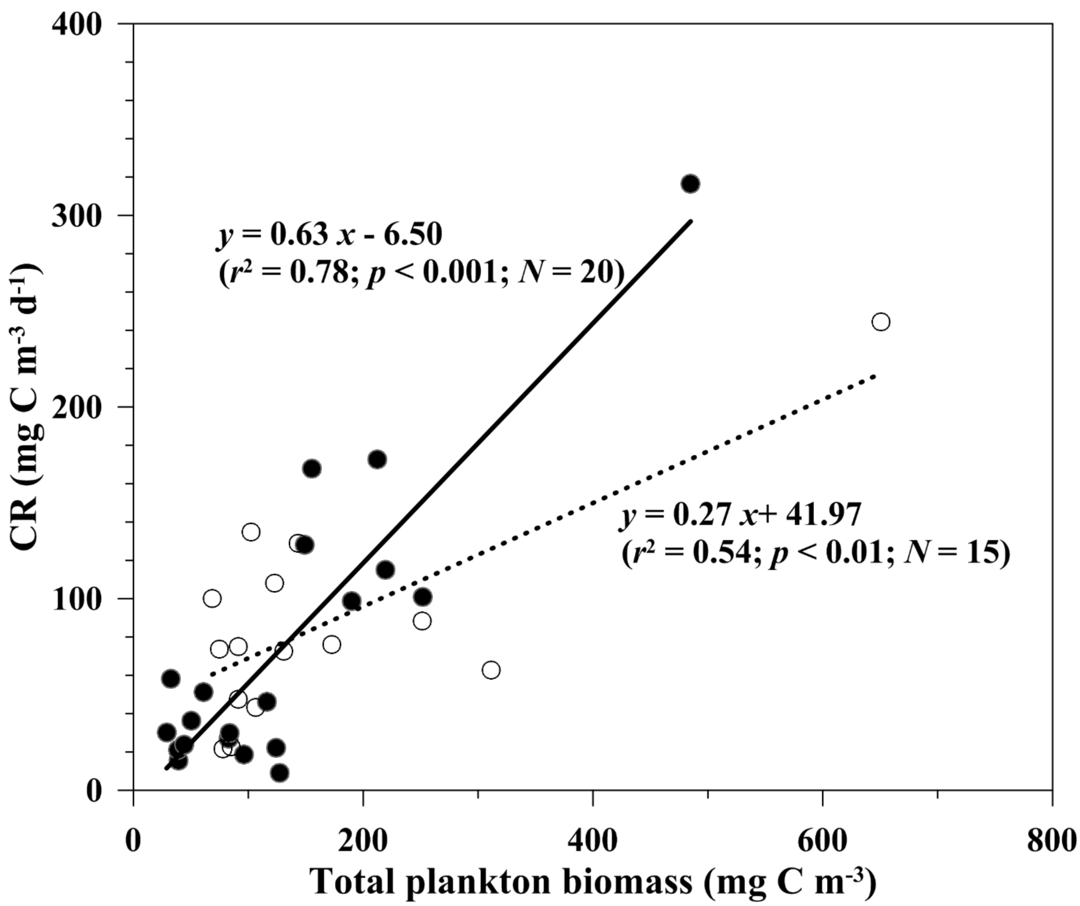

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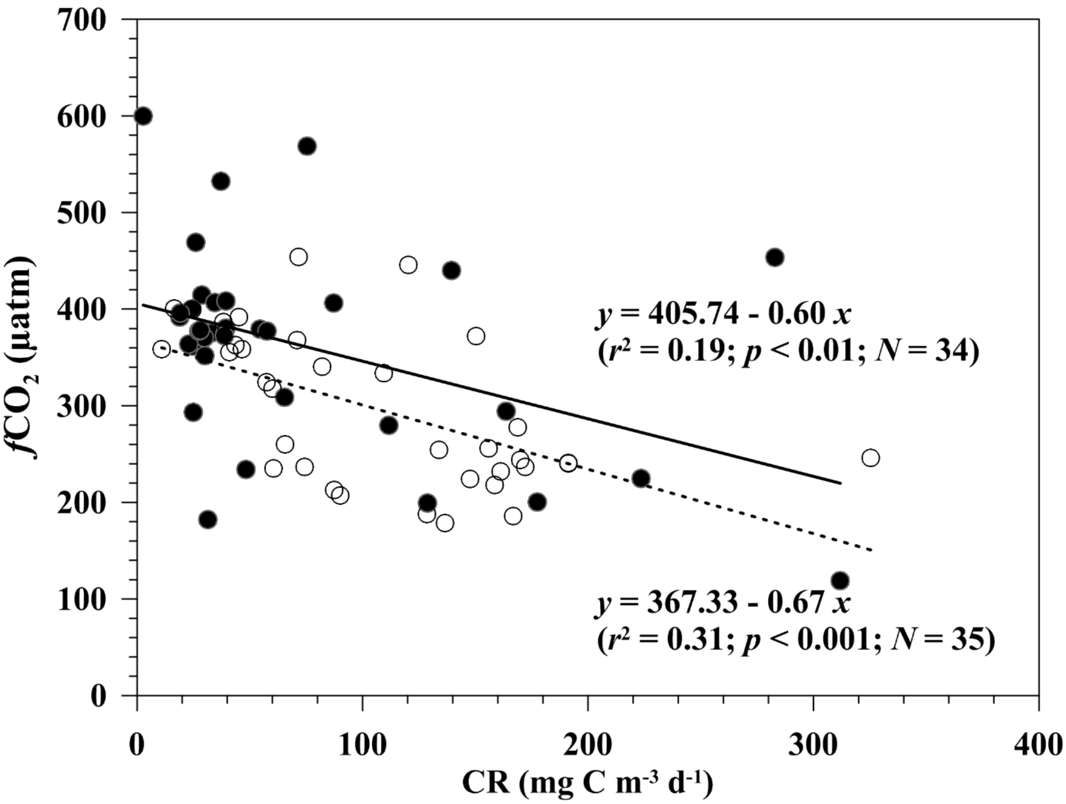

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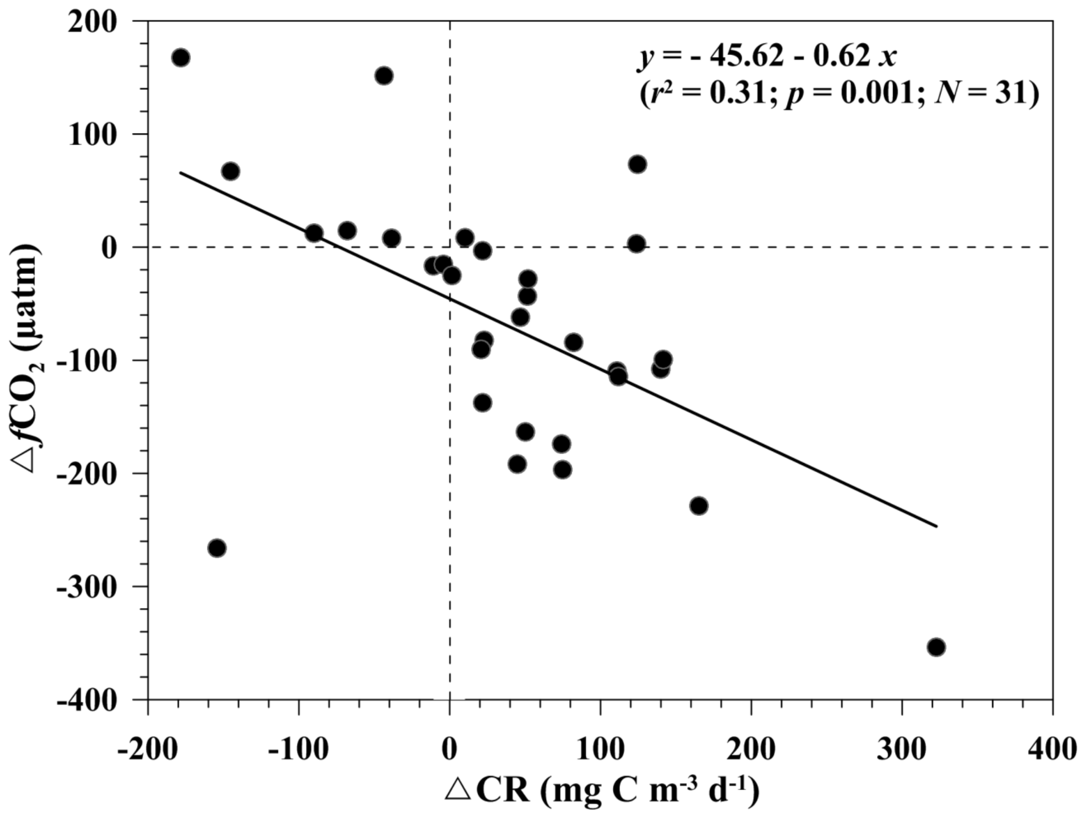

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