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Effects of flooding on organic carbon consumption in the East China Sea

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Abstract

This study was designed to determine the effects of flooding on plankton community respiration (CR) in the East China Sea (ECS). In July 2010, a devastating flood occurred in the Changjiang River; the mean monthly discharge was 60 527 $m^3 s^{-1}$. To compare, the variables were also examined in the low riverine flow of July 2009 (33 955 $m^3 s^{-1}$). During the flooding, the Changjiang diluted water (CDW) zone, the sea surface salinity (SSS) was ≤ 31 psu, covering almost two thirds of the ECS, which was approximately six times that in the non-flooding period. The mean nitrate concentration was higher in 2010 (6.2 µM) than in 2009 (2.0 µM). However, in the 2010 flood, the mean values of Chl *a* and the bacterial biomass were only slightly higher or even lower than in 2009. Surprisingly, however, the CR was still higher in the flood period than in the non-flood period, 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 activities, especially phytoplankton, at stations in the CDW zone, which were not mostly covered by low SSS in 2009. There was a huge amount of fCO_2 drawdown in the 2010 flood. These results suggested that the devastating flood in 2010 had a significant effect on the carbon balance in the ECS. This effect might become more pronounced as extreme rainfall events and flooding magnitudes increase dramatically throughout the world.

1 Introduction

The 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 has been delivered into coastal regions, thus enhancing primary productivity (e.g., Dagg et al., 2004; Nixon et al., 1996). In addition, a large quantity of particulate and dissolved organic matter is discharged through the riverine input (e.g., Wang et al., 2012). High rates of microbial metabolism associated with

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this discharge have been observed in vicinal marine environments (e.g., Hedges et al., 1994; Malone and Ducklow, 1990). The river plume 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 sea. Under the current conditions of climate change, it has become even more pronounced because of the dramatic increase in extreme rainfall events and flood magnitudes throughout the world (Christensen and Christensen, 2003; Knox, 1993; Milly et al., 2002; Palmer and Ralsanen, 2002).

The East China Sea (ECS) has an approximate area of 0.5×10^6 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, especially 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 it discharges into the ECS, freshwater mixes with seawater to form the Changjiang diluted water (CDW) zone, the salinity of which is ≤ 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 primary production (PP) (Chen et al., 2006; Gong et al., 2003). The rates of CR were also positively related to the riverine flow rates (Chen et al., 2009). However, few previous studies have shown the effects of flood on biological activities in the ECS (Chung et al., 2014; Gong et al., 2011). Historically, the threshold discharge rates in Changjiang River flooding have been estimated at 4–6 $\times 10^4$ m^3 s^{-1} (Committee, 2001). However, in recent decades, the frequency and magnitude of Changjiang River floods have increased, which have been attributed to extreme monsoon rainfall associated with climate warming (Jiang

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et al., 2007; Yu et al., 2009), suggesting that the influence of flooding on the ECS shelf ecosystem has intensified. Therefore, it is worthwhile exploring the responses of biological activities and ecological processes in the ECS to the periodic flooding of the Changjiang River.

In July 2010, a devastating 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, in a period (July 2009) when the riverine flow was low. The main objective of this study is 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.

2 Materials and methods

2.1 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 (29 June to 13 July) and 2010 (6 to 18 July) during two cruises, respectively, on the R/V *Ocean Researcher I*. The sample stations were located throughout the ECS shelf (Fig. 1). In July 2010, the mean monthly discharge from the Changjiang River reached 60 527 $m^3 s^{-1}$, which was significantly larger 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

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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. Subsamples were taken for immediate analyses (i.e., dissolved inorganic nutrients, chlorophyll *a*, and bacterial abundance) and on-board incubation of primary production and plankton community respiration (CR). The methods used to collect the hydrographic data and determine the 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 our results were published by Chung et al. (2014) and Gong et al. (2011).

2.2 Physical and chemical hydrographics

Temperature and salinity were recorded throughout the water column using a SeaBird CTD. 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 nutrients (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 data on dissolved inorganic carbon (DIC) and total alkalinity (TA) using the designed program (Lewis and Wallace, 1998). For details of the TA and DIC measurements, refer to Chou et al. (2007).

2.3 Biological variables

The water samples taken for chlorophyll *a* (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 determined fluorometrically (Turner Design 10-AU-005; Parsons et al., 1984).

The samples of heterotrophic bacteria 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 in preparation for the analysis. The heterotrophic bacteria were stained with the nucleic acid-specific dye SYBR-Green I (emission = 530 ± 30 nm) at the 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 cytometry unit (FACSAria, Becton-Dickinson Co., New Jersey, USA). Known numbers of fluorescent beads (TruCOUNT Tubes, Becton-Dickinson Co., New Jersey, USA) were simultaneously used to calculate the original cell abundance in each sample. Bacterial abundance was converted to carbon units using a conversion factor of 20×10^{-15} g C cell^{-1} (Hobbie et al., 1977; Lee and Fuhrman, 1987).

Primary production (PP) was measured by the ^{14}C assimilation method. The incubated samples were collected from three depths within Z_E at stations occupied during daylight (Gong et al., 2003; Parsons et al., 1984). The samples were pre-screened through 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 on board for 2 h 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 2N 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 also note that PP was measured only at selected stations in 2010, but it was not measured in 2009.

The plankton community respiration (CR) was measured as the decrease in dissolved oxygen (O_2) during dark incubation (Gaarder and Grann, 1927). Incubation was conducted at most stations with duplicate samples taken from several (4–6) depths within Z_E at each station. The treatment involved incubating the bottles for 24 h in a dark chamber (Chen, C.-C. et al., 2003). The difference in O_2 concentration between the initial treatment 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).

3 Results and discussion

3.1 Comparison of hydrographic patterns between flooding and non-flooding periods

In July 2010, the Changjiang River flooded to a devastating extent. The mean monthly water discharge was 60 527 $m^3 s^{-1}$, and the threshold discharge rate was 4–6 × 10^4 $m^3 s^{-1}$, making it the largest recorded flooding of the Changjiang River over the last decade (Committee, 2001). 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 2009 non-flood; the mean (±SD) values were 30.32 (±3.60) and 32.62 (±2.7) psu, respectively (Table 1). During periods of high discharge from the river, particularly during the summer, the Changjiang diluted water (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 enormous amount 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 was approximately six times larger than in the 2009 non-flood; their values were 111.7×10^3 and 19.0×10^3 km^2, respectively.

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 (±SD) values of SST in 2009 and 2010 were 26.8 (±1.7) and 26.1 (±2.2) °C, respectively. These values 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 the periods. The mean (±SD) values of M_D in 2009 and 2010 were 13.7 (±7.3) and 11.3 (±6.6 m), respectively (Table 1). However, the average M_D was shallower than the observed values of the ECS in summer (Chen et al., 2009). Even though the mean ±SD 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 the periods (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). In particular, in 2009, the Z_E in the CDW was only 16.83 m. This finding suggests that the growth of phytoplankton might be limited by the availability of light.

In general, a huge amount 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, 2009; Gong et al., 1996). This study found a higher concentration of nitrates in the ECS during flooding, mostly in the fluvial discharge of the Changjiang River. This finding was supported by the negative linear relationship between SSS and nitrate concentration of the ECS in 2010 ($r^2 = 0.37$, $p < 0.001$, $n = 37$). During the period of this study, the linear relationship was also negatively regressed between SSS and silicate concentration ($r^2 = 0.60$, $p < 0.001$, $n = 37$), but not phosphate concentration. The comparison of the 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-flood, with

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mean (±SD) values of 6.2 (±9.8) and 2. (±5.3) µM, respectively (Table 1). This finding also applied to the average nitrate values 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 in the high riverine discharge period 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 most of the elevated nitrate concentrations were observed within the CDW (Fig. 1d). In this period, the mean ±SD 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 (±SD) value of 40.4 (±22.6). This value was comparable to that of the CDW in high riverine flow of 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 (± SD) 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-flood, phytoplankton growth might have been regulated by the availability of dissolved inorganic nitrogen to a greater extent than it was in 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 US (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).

3.2 Plankton activities associated with the Changjiang River flood

Following the huge discharge of fluvial nutrients into the ECS, phytoplankton is generally abundant in the CDW region. The Chl *a* concentration in the CDW even reached bloom criteria > 20 mg Chl m^{-3} in the ECS (Chen et al., 2009, Chen, C. S. et al., 2003). Surprisingly, the phytoplankton biomass was not as high as expected even though

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a high nitrate concentration was observed in the 2010 flood. The mean (±SD) 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 in the ECS in mid-summer – July and August (Chen et al., 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. 1e and f). For example, in the 2010 flood, the maximum Chl *a* value reached 5.32 mg Chl m^{-3} in the CDW (Table 1; Fig. 1f). In the 2010 flood, the Chl *a* values were positively related to nitrate and silicate concentrations (all $p < 0.001$), but not phosphate concentrations, in the surface water. In the 2009 non-flood, the Chl *a* concentration was significantly linearly regressed with all measured nutrients: nitrate, silicate, and phosphate (all $p < 0.01$). The spatial Chl *a* distribution pattern found in this study was similar to that found in previous studies on the ECS (Gao and Song, 2005; Gong et al., 2011). However, it should be noted that the CDW zone was extensive in the 2010 flood. Nevertheless, the phytoplankton biomass in the surface water (Table 1), or average over Z_E (data not shown), did not differ significantly between 2009 and 2010. 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 observed in the ECS in summer (Chen et al., 2009). Gong et al. (2011) estimated that over the past decade, the average rate of carbon fixation during the flood was about three times higher than during the non-flooding period. During the 2010 flood, the rate reached 176.0×10^3 t C d^{-1} in the CDW (Gong et al., 2011). The abundance of phytoplankton was twice as high in the CDW than in the other regions. In the 2010 flood, the phytoplankton were predominantly diatom, especially *Chaetoceros* spp., *Rhizosolenia* spp. and *Nitzschia* spp. (Gong et al., 2011). However, the microphytoplankton assemblage was not measured in 2009. In July 2007, when the amount of freshwater discharge was similar to that in 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 *Syne-*

chococcus, were predominant in the CDW, and they showed similar spatial distribution patterns in both 2009 and 2010 (Chung et al., 2014). In addition, the phycoerthrin-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 lesser presence of *Prochlorococcus* was also observed in regions other than the CDW in both periods (Chung et al., 2014). These results imply that 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 the periods.

In summer, heterotrophic bacterioplankton are generally more abundant in the CDW of the ECS than in other regions (Chen et al., 2006, 2009). Chen et al. (2006) suggested that the growth of bacteria along the coast might be stimulated by the enormous 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-flood, the mean (±SD) values of the bacterial biomass in the surface water of the CDW and other areas were 77.5 (±55.7) and 31.0 (±18.6) $mg\,C\,m^{-3}$, respectively. Their mean (±SD) 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 significantly linearly regressed 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). Furthermore, in general, an increased amount of organic matter was delivered through fluvial discharge into the ECS during 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 in this study. The bacterial biomass in the surface water was significantly higher in

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the 2009 non-flood than in the 2010 flood, with mean (±SD) 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). In addition, the major taxa of bacterioplankton varied between both periods (C.-C. Chung's unpublished data). During the non-flooding period, cyanobacteria were predominant in more than 70 % of bacterioplankton at the selected sampling stations located either in the CDW zone or in other regions of the ECS. In the 2010 flood, its distribution was observed only at stations located in regions other than the CDW zone. In the 2010 flood, the dominant taxa of bacterioplankton in the CDW zone included cyanobacteria, favobacteria, gammabacteria, alphabacteria, and actinobacteria. A potential cause of the low 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, C.-C., 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 $\mu g\,C\,L^{-1}\,h^{-1}$ during high riverine flow (Tsai et al., 2005).

3.3 Effects of the Changjiang River flood on plankton community respiration

Plankton community respiration (CR) has been assumed 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, 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 (±SD) value of 73.2 (± 76.9) $mg\,C\,m^{-3}\,d^{-1}$ in the 2009 non-flood (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 (±SD) 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

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(±SD) values of 76.8 (±53.0) and 66.8 (±68.4) $\mathrm{mg\,C\,m^{-3}\,d^{-1}}$, respectively. However, the difference was not statistically significant ($p = 0.08$). In terms of spatial distribution, in both periods, higher CR rates were mostly observed in the CDW region, especially along the coast (Fig. 2). Nevertheless, it should be noted that the CDW widely expanded in 2010 compared to that of 2009. These results also showed that the CR in the summer of the 2010 flood was at the high end of the values observed in the ECS (Chen et al., 2006, 2009). This finding suggests that in 2010, the CR might have been enhanced by the Changjiang River flood.

To assess the biotic controls CR, the rates were regressed against the phytoplankton biomass and heterotrophic bacteria, as well as the primary production, if it was applicable. The analysis of the pooled data in each period showed that CR was significantly related to Chl *a* concentrations or bacterial biomass (all $p < 0.001$; Fig. 3). In both periods, the linear relationship was also statistically significant between CR and Chl *a* concentration or bacterial biomass, either for the surface water or for the average value over Z_E (all $p < 0.01$). In addition, in the 2010 flood, CR was significantly related to PP in the pooled data, surface water, or averaged value over Z_E (all $p \leqq 0.01$). Compared with a previous study on the ECS (Chen et al., 2009), CR ($\mathrm{g\,O_2\,m^{-3}\,d^{-1}}$) was also scaled as a power function of PP ($\mathrm{g\,O_2\,m^{-3}\,d^{-1}}$) in the 2010 flood, where $\mathrm{CR} = 5.78\mathrm{PP}^{1.24}$ ($p = 0.001$; Fig. 4). Note that the exponential (1.24) is the slope of the log-log transformation. This value is larger than the relationships reported for the ECS ($\mathrm{CR} = 0.58\mathrm{PP}^{0.46}$) and other coastal ecosystems in the world ($\mathrm{CR} = 1.1\mathrm{PP}^{0.72}$) (Chen et al., 2009; Duarte and Agustí, 1998). This finding suggests that during the 2010 flood, the CR rate might have been dependent on 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, 2009; Chen, C.-C. et al., 2003). These results suggest that the CR rate was dominated by phytoplankton and/or bacterioplankton in both the 2009 non-flood and the 2010 flood.

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Surprisingly, the mean Chl *a* value was slightly higher in 2010 than in 2009. In contrast, in this study, the bacterial biomass was significantly smaller in 2010 than in 2009 (Table 1). However, the CR rate was still higher in 2010 than in 2009. In a further analysis, the differences (i.e., 2010–2009) in the average variables over Z_E, that is, CR, Chl *a* concentration, and bacterial biomass, at the same station between two periods were compared. The values of differences in CR were significantly related to differences in Chl *a* concentration ($p < 0.001$) or bacterial biomass ($p < 0.01$; Fig. 4). 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 values (i.e., 20 of 33) of difference in CR, 15 stations had positive values of the difference in Chl *a* concentrations, but only two stations had positive values of the difference in bacterial biomass. Interestingly, the stations with positive values of Chl *a* concentration difference 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, as previously stated. However, the phytoplankton assemblage varied between both periods. Therefore, it is reasonable to assume that the differences in CR rate in both periods might have been caused by variants in the composition of the phytoplankton. Although the CR caused by different phytoplankton assemblage was not measured in this study, it was observed in various phytoplankton taxa (e.g., Lopez-Sandoval et al., 2014).

3.4 Implication of community metabolism in the coastal ecosystem

To evaluate the metabolic balance of the plankton community, the P/R ratio of primary production (PP) to CR usually serves as an index. 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 the entire water column. In the 2010 flood, the P/R ratio was in the range of 0.11 to 1.33, but in 2009, its value was not available because PP was not measured in this period. Surprisingly, the mean P/R

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ratio was similar to that in summer of the ECS, with a mean ±SD value of 0.42 ± 0.33 (Chen et al., 2009). This value however was much lower than the P/R ratio (= 1.17) 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. It has been suggested that to support high CR, in addition to autochthonous organic carbon, tremendous amounts of allochthonous organic materials discharged from the Changjiang River into the ECS shelf during high-flow summer might be an important external source (Cauwet and Mackenzie, 1993; Chen et al., 2009; Deng et al., 2006). This result also suggests that in the 2010 flood, the ECS shelf ecosystems were net heterotrophic. A heterotrophic ecosystem was found in the ECS in summer and in other seasons (Chen et al., 2006, 2013; Chen, C.-C., 2003). A low P/R ratio (i.e., < 1) was also widely observed in coastal ecosystems (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 dissolved in the surface water was in the range of 118.7–599.8 µatm, with mean ±SD 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 (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, ranging from 178.7 to 454.2 µatm (Table 1). It is well known that fCO_2 is temperature dependent, and it decreases 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-flood and the 2010 flood might be trivial 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 been suggested to be relatively minor compared to the inter-annual variation of fCO_2 in the spring (Chen et al., 2013). To evaluate, 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 endmembers (both TA and DIC = 1743 µmol kg^{-1}). The surface data at St. K,

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shown as the bottom right-hand side station in Fig. 1, were selected to represent the seawater end-members (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 result shows that the effect of mixing freshwater and seawater on fCO_2 was nearly the same in both periods. However, a large variation of fCO_2 in the surface water were estimated; it varied from 439.8 to 375.4 µatm within a salinity range of 20.38–33.96. 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) covered almost two thirds 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 of the drawdown of huge amounts of fCO_2 in the surface water during periods of flooding. High primary production was indeed observed in the 2010 flood (Table 1). Gong et al. (2011) also estimated that over the past decade, the carbon fixation rate during flooding was about three times higher than in non-flooding. However, no significant relationship was found between fCO_2 and PP in the 2010 flood, which might have been because PP data were rare in this period. 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 huge drawdown of fCO_2 in the 2010 flood might be associated with vigorous phytoplankton activity. Furthermore, negative linear regressions were observed between fCO_2 and CR in the surface water during both the 2009 non-flood ($p < 0.01$) and the 2010 flood ($p < 0.001$; Fig. 6). Significant linear relationships were also found using pooled data from each period (all $p < 0.001$). CR has been assumed an integrated response in plankton activities. 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. 7). As previously stated, compared to the 2009 non-flood, 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 covered by low SSS in the 2009 non-flood.

4 Conclusion

The riverine run-off has a profound effect on organic carbon production and consumption in the coastal ecosystems. 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, with a mean monthly discharge of $60\,527\,m^3\,s^{-1}$. This event provided an opportunity to investigate the effects of flooding on plankton community respiration (CR) in the ECS shelf ecosystem. A comparative analysis was conducted on variables, including physical, chemical and biological parameters, in the July 2010 flood and in July 2009, when the riverine flow was low (mean monthly values = $33\,955\,m^3\,s^{-1}$). During the flood, a tremendous amount of freshwater was discharged into the ECS. The Changjiang diluted water (CDW) zone, where sea surface salinity (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-flood; their values were 111.7×10^3 and $19.0 \times 10^3\,km^2$, respectively. 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 than in the 2009 non-flood, with mean ±SD values of 6.2 ± 9.8 and $2.0 \pm 5.3\,\mu M$, respectively. Nevertheless, the phytoplankton biomass in the surface water or averaged over the euphotic zone (Z_E) showed no significant difference between 2009 and 2010. However, in the 2010 flood, primary production in the surface water was high, with mean ±SD values of $62.1 \pm 33.8\,mg\,C\,m^{-3}\,d^{-1}$. Gong et al. (2011) estimated that the average rate of carbon fixation during the flood was 176.0×10^3 t C d^{-1}, which was about three times higher than during non-flooding over the past decade. Phytoplankton abundance was twice as high in the CDW than in other regions. In the 2010 flood, the phytoplankton was predominately diatom, especially *Chaetoceros* spp., *Rhizosolenia* spp. and *Nitzschia* spp., (Gong et al., 2011). A previous study showed that during non-flooding, phytoplankton assemblage in the CDW, in addition to diatoms, were predominately dinoflagellates, coccolithophorids, and green algae (Chien, 2009). Surprisingly, the bacterial biomass in the surface water was significantly higher in the 2009 non-flood than in the 2010 flood, with mean ±SD values of 39.8 ± 33.7 and 20.4 ± 16.5 mg C m^{-3}, respectively.

In this study, the mean value of Chl *a* was slightly higher in 2010 than in 2009, and the bacterial biomass was significantly lower in 2010 than in 2009. Interestingly, CR was still higher in the 2010 flood than in the 2009 non-flood, 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 differences (i.e., 2010–2009) in the variables averaged over Z_E, such as CR, Chl *a* concentration, and bacterial biomass, at the same station in two periods were compared. The values of difference in CR were significantly related to the values of differences in Chl *a* concentration. This result suggested that higher CR in the 2010 flood might be attributed to a higher biomass with variant phytoplankton assemblage, especially in stations located within the CDW region, most of which were not covered by low SSS in the 2009 non-flood. A negative linear relationship was also found between the differences (i.e., 2010–2009) in surface water variables of CR vs. $f\mathrm{CO_2}$. This finding implies that a tremendous amount $f\mathrm{CO_2}$ of was absorbed by vigorous photosynthesis during the flood period. Overall, these results suggest that plankton activity flourished in the huge amount of dissolved inorganic nutrients in the riverine discharge during the flood. This effect was especially pronounced at stations not previously covered by low SSS. This finding indicates 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 with mean ±SD in parentheses given for non-flood (2009) and flood (2010) periods. Variables include salinity (SSS; psu), temperature (SST; °C), 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 comparison between 2009 and 2010, and the results are indicated herein.

Variables	2009	2010
Z_E	1.3–190.6 (38.9 ± 36.4)	10.1–82.2 (33.4 ± 17.3)
M_D	5–37 (13.7 ± 7.3)	4–35 (11.3 ± 6.6)
SSS	23.80–34.11 (32.62 ± 2.07)	19.33–34.27 (30.32 ± 3.60)[a]
SST	23.3–29.6 (26.8 ± 1.7)	21.0–30.0 (26.1 ± 2.2)
fCO_2	118.7–599.8 (362.9 ± 101.2)	178.7–454.2 (297.6 ± 79.0)[a]
NO_3^-	0.0–24.3 (2.0 ± 5.3)	0.0–37.6 (6.2 ± 9.8)[a]
PO_4^{3-}	0.00–0.83 (0.13 ± 0.17)	0.00–1.71 (0.17 ± 0.30)
SiO_4^-	1.5–24.5 (5.8 ± 5.9)	0.6–36.4 (6.4 ± 7.8)
Chl *a*	0.12–4.41 (0.98 ± 1.52)	0.03–5.32 (1.26 ± 1.27)
BB	10.6–184.8 (39.8 ± 33.7)	3.6–90.2 (20.4 ± 16.5)[b]
PP	–	10.0–111.3 (62.1 ± 33.8)
CR	2.7–311.9 (73.2 ± 76.9)	10.9–325.3 (105.6 ± 66.7)[a]

–: no data;
[a] $p < 0.01$;
[b] $p < 0.001$.

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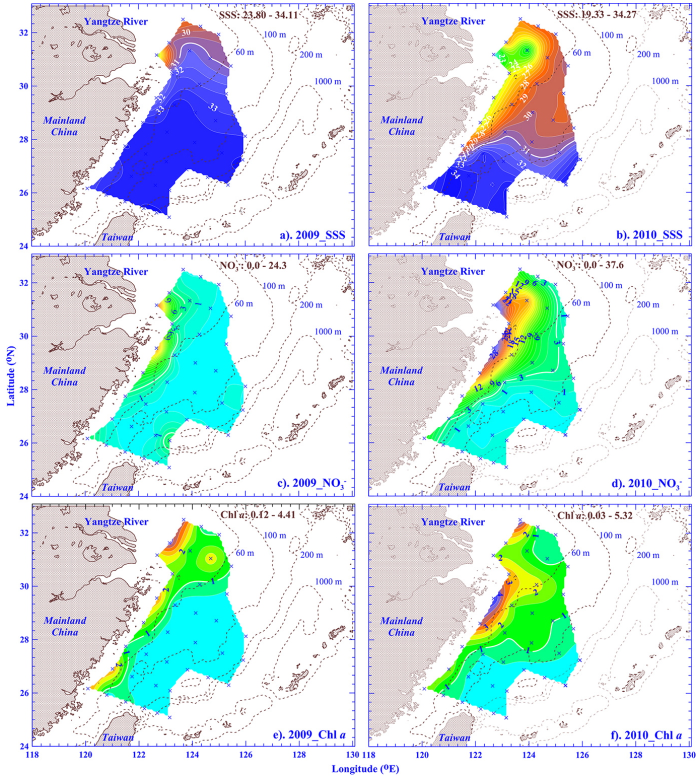

Figure 1. Contour plots of salinity (SSS), nitrate (NO_3^-), and chlorophyll *a* (Chl *a*) in the surface water (2–3 m) of the ECS in non-flooding (2009) and flooding (2010) periods. Bottom depth contours are shown as dashed lines, both here and in Fig. 2. The sampling stations in both periods are marked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

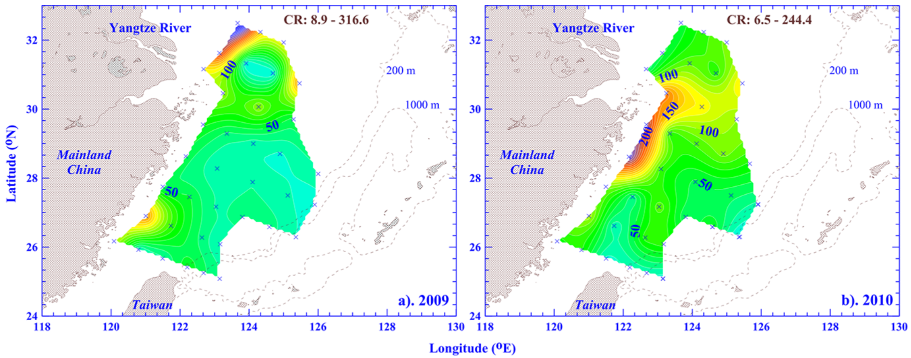

Figure 2. Contour plots of plankton community respiration (CR; $mg\,C\,m^{-3}\,d^{-1}$) over the euphotic zone of the ECS in **(a)** non-flooding (2009) and **(b)** flooding (2010) periods. The contour interval is $10\,mg\,C\,m^{-3}\,d^{-1}$. The range of CR is shown at the top of each panel.

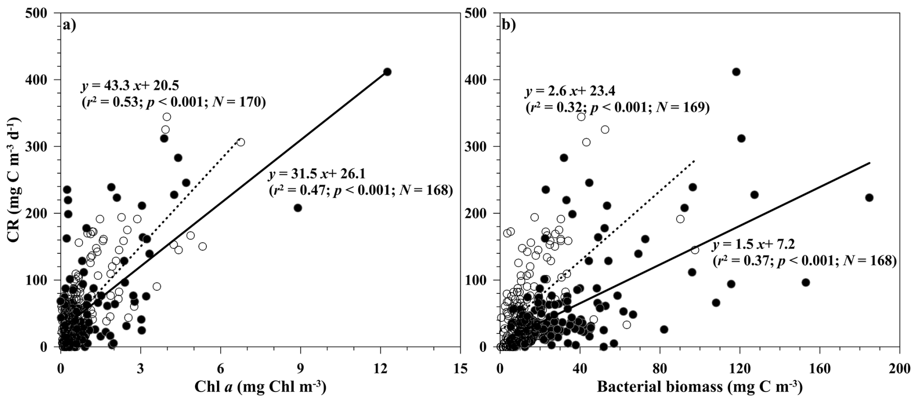

Figure 3. Relationships between plankton community respiration (CR; $mg\,C\,m^{-3}\,d^{-1}$) and **(a)** chlorophyll *a* concentration (Chl *a*; $mg\,Chl\,m^{-3}$) and **(b)** bacterial biomass ($mg\,C\,m^{-3}$) for all data from periods of non-flooding (2009; •) and flooding (2010; ∘). Linear regressions of data from 2009 (solid lines) and 2010 (dashed lines); r^2 and p values are included.

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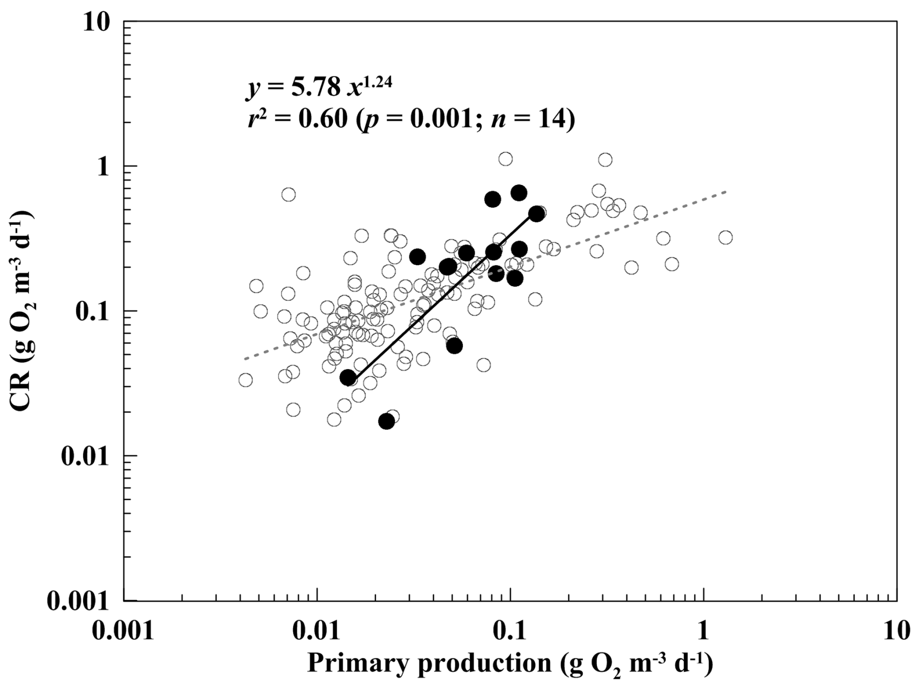

Figure 4. Log–log relationships between averaged volumetric rates of primary production (PP, converted to O_2 units) vs. volumetric rates of CR in 2010 (•). Please note the log scale in both axes. The solid line show the relationship as a power function of PP. For comparison, the estimated power functions of CR vs. PP ($CR = 0.58PP^{0.46}$) in summer (◦) in the ECS is shown as gray line (Chen et al., 2009).

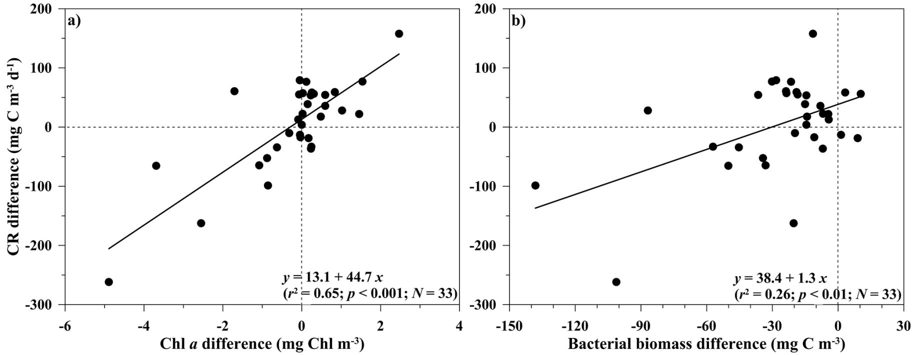

Figure 5. Differences between 2010 and 2009 in plankton community respiration (CR; $mg\,C\,m^{-3}\,d^{-1}$) vs. **(a)** chlorophyll *a* (Chl *a*; mg Chl m^{-3}) and **(b)** bacterial biomass ($mg\,C\,m^{-3}$) over the euphotic zone at the same station. Both r^2 and p values of linear regression (solid line) are included. For reference, the vertical and horizontal dashed lines represent the differences in variables equal to zero.

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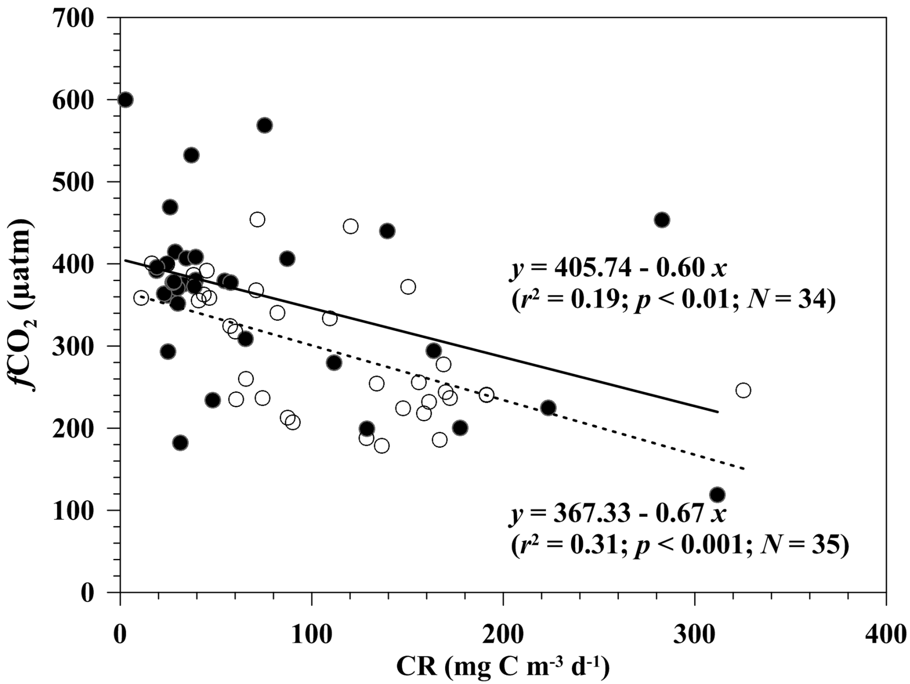

Figure 6. Relationships between the fugacity of CO_2 (fCO_2) and plankton community respiration (CR) in the surface water in 2009 (•; solid line) and 2010 (◦; dashed line). Both p and r^2 values of linear regression are shown.

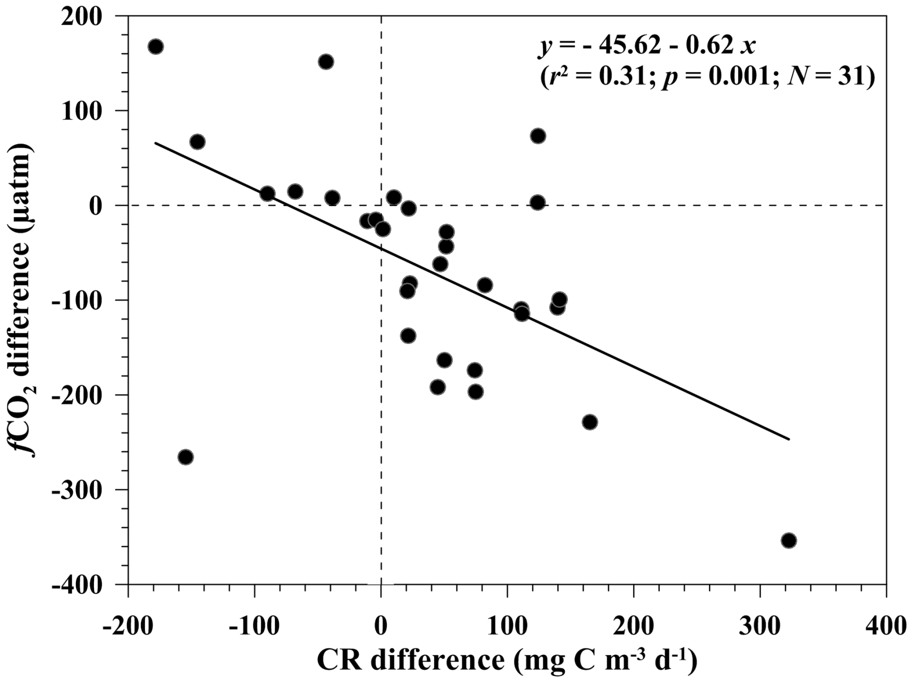

Figure 7. Differences between 2010 and 2009 in fCO_2 (µatm) and plankton community respiration (CR; $mg\,C\,m^{-3}\,d^{-1}$) in the surface water at the same station. Both r^2 and p values of linear regression (solid line) are included. For reference, the vertical and horizontal dashed lines represent the differences in variables equal to zero.

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