The large variation in organic carbon consumption in spring in the East China Sea

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Abstract. A tremendous amount of organic carbon respired by plankton communities has been found in summer in the East China Sea (ECS), and this rate has been significantly correlated with fluvial discharge from the Changjiang River. However, respiration data has rarely been collected in other seasons. To evaluate and reveal the potential controlling mechanism of organic carbon consumption in spring in the ECS, two cruises covering almost the entire ECS shelf were conducted in the spring of 2009 and 2010. These results showed that although the fluvial discharge rates were comparable to the high riverine flow in summer, the plankton community respiration (CR) varied widely between the two springs. In 2009, the level of CR was double that of 2010, with mean (±SD) values of 111.7 (±76.3) and 50.7 (±62.9) mg C m⁻³ d⁻¹, respectively. The CR was positively correlated with concentrations of particulate organic carbon and/or chlorophyll a (Chl a) in 2009 (all p < 0.01). These results suggest that the high CR rate in 2009 can be attributed to high planktonic biomasses. During this period, phytoplankton growth flourished due to allochthonous nutrients discharged from the Changjiang River. Furthermore, higher phytoplankton growth led to the absorption of an enormous amount of fugacity of CO₂ (fCO₂) in the surface waters, even with a significant amount of inorganic carbon regenerated via CR. In 2010, even more riverine runoff nutrients were measured in the ECS than in 2009. Surprisingly, the growth of phytoplankton in 2010 was not stimulated by enriched nutrients, and its growth was likely limited by low water temperature and/or low light intensity. Low temperature might also suppress planktonic metabolism, which could explain why the CR was lower in 2010. During this period, lower surface water fCO₂ may have been driven mainly by physical process(es). To conclude, these results indicate that high organic carbon consumption (i.e. CR) in the spring of 2009 could be attributed to high planktonic biomasses, and the lower CR rate during the cold spring of 2010 might be likely limited by low temperature in the ECS. This further suggests that the high inter-annual variability of organic carbon consumption needs to be kept in mind when budgeting the annual carbon balance.

1 Introduction

The annual carbon budget is crucial in determining whether a system is a carbon sink or source. This issue is especially important in high productivity coastal and shelf ecosystems, which account for one-fifth to one-third of global marine primary productivity (e.g. Walsh, 1991; Wollast, 1998). However, controversy remains over carbon sinks and sources in coastal and shelf ecosystems due to the complexity of their physical and biogeochemical processes (e.g. de Haas et al.,
Estimation of the annual carbon budget will depend on the production and consumption of organic carbon, although it also will be affected by other processes, e.g. transporting from terrestrial sources, mixing with other water bodies, benthic processes, etc. Organic carbon production, i.e. primary productivity, has been widely measured at a spatiotemporal scale around the world oceans (e.g. Falkowski and Woodhead, 1992; Thornton, 2012 and citation therein). Furthermore, highly seasonal and annual variability of organic carbon consumption make it even more difficult to budget the carbon balance (e.g. Chen et al., 2009; Smith and Kemp, 1995).

There is also a controversial debate between carbon sinks or sources in the East China Sea (ECS) ecosystem, one of the largest continental shelves in the world. By using the fugacity of CO$_2$ ($f$CO$_2$), previous studies showed that remarkably high levels of atmospheric CO$_2$ were drawndown into the surface waters of the ECS (Peng et al., 1999; Tsunogai et al., 1999; Wang et al., 2000). A similar result was also observed in summer, with flourishing planktonic activities; however, supersaturated CO$_2$ has regenerated in the subsurface waters below pycnocline in the ECS (Chen et al., 2006; Chou et al., 2009). Therefore, as Chen et al. (2006) propose, whether the ECS shelf acts as a carbon sink or source might depend on the amount of regenerated inorganic carbon in the subsurface waters released through prevailing physical forces. Furthermore, it has also been validated that the organic carbon consumption rate correlates with planktonic activities, which is in turn proportional to the fluvial discharge rate (e.g. Chen et al., 2009). These results also indicate that organic carbon respired by the plankton community serves as an important factor in carbon cycling processes, but may vary seasonally under different physical and biogeochemical conditions. Since most studies on organic carbon consumption in the ECS were performed in summer (Chen et al., 2003, 2006, 2009), studies on other seasons are needed to conclusively reveal the annual carbon budget.

To explore this phenomenon further, data from two spring cruises were used to examine the roles and the potential controlling mechanisms of organic carbon consumption. Plankton community respiration (CR) was taken as the rate of organic carbon consumption in this study. To evaluate this difference, physical and chemical parameters and biological activities were analyzed and compared to elucidate the potential causes for the spatial and inter-annual variations of CR. In addition, the relationship between CR and $f$CO$_2$ was examined to reveal the contribution of the plankton community to the $f$CO$_2$ variation in spring.
2.3 Nutrients, chlorophyll a, particulate organic carbon, and the fugacity of CO₂ ($f$CO₂)

Water samples for dissolved inorganic nutrients (e.g. nitrate, phosphate, and silicate) were collected from every sampling depth with 100 mL polypropylene bottles and were frozen immediately with liquid nitrogen. A custom-made flow-injection analyzer was used for nitrate, phosphate, and silicate analysis with detection limit of 0.3, 0.01, and 0.5 µM, respectively (Gong et al., 2003). Integrated values for nitrate and other variables in the water column above the epilimnion (Gong et al., 2003). Integrated value divided by Zₑ was estimated from vertically integrated value divided by Zₑ, and this calculation was also carried out with other variables.

Chlorophyll a (Chl a) concentration was measured with a Sea Tech fluorometer attached to the SeaBird CTD for a continuous profile of in vivo fluorescence and calibrated by in vitro fluorometry. Water samples (2 L) for in vitro Chl a measurement 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). If applicable, Chl a was converted to carbon units using a C : Chl value of 52.9, estimated from the shelf waters of the ECS (Chang et al., 2003).

At selected stations, 2 L of water samples for particulate organic carbon (POC) were filtered through a Whatman 25 mm GF/F filter, wrapped in aluminum foil, and then stored at −20°C until analysis. Both the filter and aluminum foil were prebaked at 500°C for 2 h. After fuming the filters with HCl, the POC on the filters was measured using an elemental analyzer (Elementa, Vario EL-III, Germany; Hung et al., 2010).

The fugacity of CO₂ in the surface waters was calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA) data using the designed program (Lewis and Wallace, 1998). For details on TA and DIC measurements, refer to Chou et al. (2007).

2.4 Primary production

Primary production was measured by the $^{14}$C assimilation method (Gong et al., 1999; Parsons et al., 1984). Water samples were collected from three depths within Zₑ at selected stations. Samples were prescreened through 200 µm woven mesh (Spectrum), and inoculated with $^{14}$CO$_3^-$ (final conc. 10 µCi mL$^{-1}$) in 250 mL clean polycarbonate bottles (Nalgene). Samples were incubated on board for 2–4 h in chambers filled with running surface seawater and illuminated by fluorescent bulbs with a light intensity corresponding to the in situ irradiance levels (Gong et al., 1999). Following retrieval, samples were filtered on GF/F filters and acidified overnight after the addition of 0.5 mL 2N HCl. Following immersion in 10 mL of scintillation cocktail (Ultima Gold, Packard), total activity on the filter was counted in a liquid scintillation counter (Packard 2700TR). The results of photosynthesis–irradiance curves were used to calculate primary production for stations, with incubation performed (refer to Gong et al. (1999) for details). To estimate the euphotic zone-integrated primary production at stations where incubation was not performed, an empirical function was applied (please refer to Gong and Liu (2003) for details).

2.5 Plankton community respiration (CR) and statistical analysis

The CR was measured as the decrease in dissolved oxygen (O₂) during dark incubation (Gaarder and Grann, 1927). Incubation was conducted at most of the stations in the ECS, with duplicate samples taken from 2 to 6 discrete depths within Zₑ at each station. Treatment samples were siphoned into 300 mL biological oxygen demand bottles. The treatment involved incubating bottles for 24 h in a dark chamber filled with running surface water, with maximum temperature changes (mean ± SD) of 1.89 ± 1.70°C and 3.33 ± 2.52°C during each incubations in 2009 and 2010, respectively. Temperature differences between top and bottom of Zₑ in all incubation stations were also small with mean (± SD) values of 1.58 (±1.30)°C and 0.91 (±1.20)°C in 2009 and 2010, respectively. Concentration of O₂ was measured by a direct spectrophotometry method with a precision of 0.02 mg l$^{-1}$ (Chen et al., 2007; Pai et al., 1993). The difference in O₂ concentration between initial and dark treatment was used to compute the CR (see Chen et al. (2003) for details). To convert respiration from oxygen to carbon units, a respiration quotient (RQ) of 1 was assumed (Hopkinson Jr., 1985; Parsons et al., 1984).

The software SigmaStat (version 3.5, Systat Software, Inc.) was used for the analysis of simple and multiple linear regressions, for analysis of variance (ANOVA), and for the Mann–Whitney Rank Sum test for group comparison.

3 Results and discussion

3.1 Hydrographic patterns in the East China Sea (ECS) in spring

The ECS shelf ecosystem is strongly influenced by complex and dynamic physical forces, including coastal river discharge, intrusions of the Yellow Sea waters, the Taiwan Strait waters, and the Kuroshio waters as well as the alternating monsoons (e.g. Liu et al., 2003). Regardless of these complexities, a general physical distribution pattern can be observed in the ECS: both surface seawater temperature (SST) and salinity (SSS) increase from the inner shelf toward the slope (Gong et al., 1996; Tseng et al., 2000). Spatially, the variation of SST and SSS is predominantly contributed by
the coastal river discharge, especially from the Changjiang (aka Yangtze River).

The largest variation of SST and SSS was consistent with periods of high river flow in late spring to early summer in the ECS (Chen et al., 1994; Tseng et al., 2000). High fluvial discharge was also observed in both spring seasons included in this study, and can be demonstrated in the large area of the Changjiang Diluted Water (CDW; SSS ≤ 31.0), which is assumed to be an index of riverine runoff (refer to Chen et al., 2009 for details). The area of CDW for 2009 (23 638 km²) and 2010 (19 907 km²) in this study were larger than the mean area of CDW (15 604 km²) in summer observed in a previous study (Chen et al., 2009). As expected, the increasing trend of SST and SSS from the inner shelf to the slope was also found in both spring seasons included this study, with the lowest values observed in the Changjiang plume region (Fig. 2). This phenomenon was caused by tremendous fluvial discharge from the Changjiang River, which can be verified from the positively linear relationship between SSS and SST in both study periods (all p < 0.001).

Even with a similar distribution pattern, larger spatial deviations for SST and SSS were observed in 2010 than for 2009 (Table 1; Fig. 2). The values of SST and SSS in 2009 were in the range of 15.7–25.3 °C (mean ± SD = 19.4 ± 2.3 °C) and 27.93–34.53 (mean ± SD = 32.61 ± 1.93), respectively (Table 1; Fig. 2a, b). Their values in 2010 were in the range of 10.6–25.3 °C (mean ± SD = 16.9 ± 4.7 °C) and 18.35–34.76 (mean ± SD = 32.20 ± 3.46), with SST significantly lower in 2010 than in 2009 (Table 1; Fig. 2c, d). It is worth noting that, in 2010, the lowest SSS (18.35) was only observed at St. 19A. However, the mean ± SD values of SSS in CDW in 2009 and 2010 were similar, with values of 29.27 ± 10.6–25.3 °C (mean ± SD = 31.0 ± 24.2) and 31.0–25.3 °C (mean ± SD = 32.61 ± 1.93), respectively (Table 1). Inter-annual variations for SST and SSS were observed in 2010 than for 2009 (p < 0.001). These results indicate that nutrient input, the plankton communities (i.e. biomass and rates) and photosynthetically active radiation (PAR; E m m⁻² s⁻¹) is provided for reference. The Mann–Whitney Rank Sum test was applied for variable comparison between 2009 and 2010, and the results are indicated herein.

Comparing data of two spring periods, the surface water nitrate was significantly lower in 2009 than in 2010, with values in the range of undetectable – 25.3 µM (mean ± SD value = 3.1 ± 5.8 µM) and undetectable – 61.3 µM (mean ± SD value = 10.5 ± 14.4 µM), respectively (p < 0.005; Fig. 3a, c). The mean value of average nitrate concentration over the euphotic zone in 2009 and 2010 were 3.6 µM and 10.1 µM, respectively (p = 0.14; Table 1). Interestingly, a previous study showed that the nutrient concentration was positively related to the area of CDW in summer (Chen et al., 2009). Nutrient concentration, however, was relatively lower in 2009, even with the larger CDW area, when compared to 2010. This implies that growth of various plankton communities might be at different stages of bloom between 2009 and 2010 following the intrusion of riverine waters enriched with nutrients and organic matter.

### Table 1. Range of different variables with mean ± standard deviation (in parentheses) in surface water (2–3 m) and averaged values over euphotic depth (Zₑ; m) in the ECS in the spring of 2009 and 2010. Surface water variables include water temperature (SST; °C), salinity (SSS), and fugacity of CO₂ (f/CO₂; µatm). Variables of averaged value include nitrate (NO₃⁻; µM), phosphate (PO₄³⁻; µM), silicate (SiO₂⁻; µM), chlorophyll a (Chl a; mg Chl m⁻³), particulate organic carbon (POC; mg C m⁻³), primary production (PP; mg C m⁻³ d⁻¹), and plankton community respiration (CR; mg C m⁻³ d⁻¹). Values of Zₑ and mixed layer depth (Mₑ; m) are also shown. In addition, photosynthetically active radiation (PAR; E m⁻² s⁻¹) is provided for reference.

<table>
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<tr>
<th>Year</th>
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<td></td>
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<tr>
<td>PAR</td>
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<td>(19.4 ± 2.3)</td>
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<td>SSS</td>
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<td>(32.61 ± 1.93)</td>
<td>18.35–34.76</td>
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<td>f/CO₂</td>
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<td>(269.6 ± 55.3)</td>
<td>199.7–400.3</td>
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<td>PO₄³⁻</td>
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<td>SiO₂⁻</td>
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<td>Chl a</td>
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<td>(1.8 ± 2.0)</td>
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<td>(227.5 ± 141.9)</td>
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<td>–</td>
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<tr>
<td>CR</td>
<td>15.2–307.3</td>
<td>(111.7 ± 76.3)</td>
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*: no data; *: p < 0.05; **: p < 0.001.
than $Z_E$ in 2009, but the difference was not statistically significant. The $M_D$ was slightly larger than $Z_E$ in 2010 with mean ± SD values of 31.0 ± 24.2 m and 28.3 ± 20.5 m, respectively (Table 1). Overall, the $M_D$ was lower than or close to $Z_E$ in this study. For comparison, the biomass and rate of plankton communities were therefore integrated over $Z_E$, since most of them were measured within $Z_E$.

Phytoplankton is one of the major plankton communities and responds instantaneously following intrusion of enriched nutrient diluted water. In the ECS, previous studies found a higher biomass of phytoplankton in the CDW during high riverine flow periods in summer, with a mean value of 3.3 mg Chl m$^{-3}$ (Gong and Liu, 2003; Gong et al., 2003). The surface water Chl $a$ showed a similar trend, with the highest value found in the CDW in 2009 of this study (Fig. 3b). The values were in the range of 0.20–10.96 mg Chl m$^{-3}$ with a mean ± SD value of 1.81 ± 2.36 mg Chl m$^{-3}$ during this period.

The mean Chl $a$ value over the $Z_E$ was almost the same as that of surface water (Table 1). Even though the mean value was not as high as the 3.3 mg Chl m$^{-3}$ value observed during the peak summer season, the highest value (10.96 mg Chl m$^{-3}$) was comparable to that measured in summer (Gong and Liu, 2003; Gong et al., 2003) and in late spring (Hung et al., 2009). Moreover, the Chl $a$ spatial trend was similar to surface water nitrate distribution in the spring of 2009 (Fig. 3a, b). One would therefore expect that the phytoplankton biomass would be associated with available nutrients during this study period. This assumption was confirmed by the positively linear relationship found between Chl $a$ and nitrate concentrations in the surface waters in 2009 (Fig. 5a; $p < 0.001$). It was also supported by linear correlations observed between Chl $a$ and phosphate or silicate concentrations of the surface waters (Fig. 5b; $p < 0.001$). In addition to surface water variables, linear regressions were also statistically significant between the averaged values over $Z_E$ of Chl $a$, on the one hand, and nitrate or silicate concentrations, on the other, in the spring of 2009 (data not shown; $p < 0.001$). These results all suggest that high phytoplankton biomass might be enhanced by dissolved inorganic nutrients, enriched from the intrusion of riverine water into the ECS in this period (Fig. 5).

The distribution pattern between SSS and nutrients (e.g. nitrate, phosphate, and silicate) was similar in the spring of 2009 and that of 2010 (Figs. 2, 3, and 4a, c, d), and a similar trend was also found between SSS and Chl $a$ in the surface.
Fig. 3. Contour plots of nitrate and chlorophyll a (Chl a) in the surface waters of the ECS in 2009 (a), (b) and 2010 (c), (d). The contour intervals of nitrate and Chl a are 2 µM and 1 mg Chl m$^{-3}$, respectively.

water in 2009 (Fig. 4b). Surprisingly, the spatial trend was somewhat different in surface water Chl a in 2010, and the higher value was observed in the middle shelf (Fig. 3d). In the spring of 2010, the surface water Chl a value was in the range of 0.03–2.48 mg Chl m$^{-3}$ with a mean ± SD value of 1.03 ± 0.72 mg Chl m$^{-3}$. Although nitrate concentrations were higher in 2010 than in 2009, both mean Chl a values in the surface waters and averaged over $Z_E$ were relatively low in 2010 compared to 2009. However, this difference was statistically insignificant (Fig. 3b, d; Table 1). This result suggests that nitrate availability might not have limited growth of phytoplankton in the spring of 2010, which can explain why phytoplankton biomass did not increase with nitrate concentration increasing in this period (Fig. 5a). Besides available dissolved inorganic nitrogen, phytoplankton growth limited by phosphate has been observed in the ECS, especially in the CDW (Chen et al., 2004; Gong et al., 1996; Harrison et al., 1990). However, this might not be the case since the mean ± SD value of phosphate in the surface water in the CDW was as high as 0.85 ± 0.77 µM in 2010. Furthermore, the mean molar ratio of N/P in the surface waters was 17.5 for the stations around the CDW regions (e.g. Sts. 19 and 21). These results indicate that dissolved inorganic nutrients may not limit growth of phytoplankton in terms of either availability or N/P molar ratio in 2010, especially in the CDW.

Beyond nutrients, phytoplankton growth may have been regulated by temperature, light intensity, and/or herbivorous grazers. Among the analyzed variables, SST was significantly lower in 2010 (mean = 16.9 °C) than that in 2009 (mean = 19.4 °C; Table 1). Moreover, the mean SST was much lower in the CDW region in 2010 (mean = 12.2 °C) than in 2009 (mean = 18.0 °C; Fig. 2a, c). To explore this further, Chl a concentrations in the surface waters were positively and negatively correlated, respectively, with SST < 15 °C and ≥ 15 °C in 2010 (Fig. 6). The positive linear regression found in SST < 15 °C indirectly showed evidence that the growth of phytoplankton might be limited by cold temperature, but not nutrient availability (mean value = 20.9 µM; Fig. 5) in 2010.

In addition to SST and inorganic nutrients, light intensity might be another important factor regulating phytoplankton growth. The mean value of PAR in the water surface in 2010 (34.4 E m$^{-2}$ d$^{-1}$) was about half of that in 2009 (60.9 E m$^{-2}$ d$^{-1}$; Table 1; $p < 0.001$). This suggests that the lower Chl a in 2010 might be strongly associated with the lower light intensity during this period. The effect of light
intensity on primary production (PP) in aquatic ecosystems is well known, and PP usually increases hyperbolically with an increase in light intensity (Kirk, 1994). As stated above, a previous study showed that the highest PP, seasonally, was observed in summer with mean values of integrated PP and PAR of about 1000 mg C m$^{-2}$ d$^{-1}$ and 79.9 E m$^{-2}$ d$^{-1}$, respectively (Gong et al., 2003). The mean (±SD) values of integrated PP and averaged PP over $Z_E$ were 485.9 (±571.9) mg C m$^{-2}$ d$^{-1}$ and 17.8 (±15.9) mg C m$^{-3}$ d$^{-1}$, respectively, in the spring of 2010 (Table 1). This mean integrated PP value was only about half of that observed during the high production season in summer (Gong et al., 2003). Light limitation on phytoplankton growth was even more critical due to a larger $M_D$ (31.0 m) and smaller $Z_E$ (28.3 m) in the spring of 2010 (Table 1). To conclude, these results imply that the growth of phytoplankton was limited by both the cold water temperature and low light intensity in spring of 2010. This can explain why the phytoplankton biomass (i.e. Chl $a$) was lower in 2010 than in 2009 although there were more available nutrients in the spring of 2010 (Table 1).

3.3 High organic carbon consumption in spring 2009

Plankton community respiration (CR) provides an integrated rate measurement of biotic organic carbon consumption in aquatic ecosystems (Calbet and Landry, 2004; del Giorgio and Duarte, 2002; Hernández-León and Ikeda, 2005; Hopkinson Jr. et al., 1989). Previous studies have shown that the CR was mostly attributed to bacterioplankton and/or phytoplankton, and the contribution by planktonic protozoa was trivial in the ECS (Chen et al., 2003, 2006, 2009). As stated above, the mean Chl $a$ values were relatively higher in 2009 than in 2010, both in the surface waters and in the averaged value over $Z_E$ (Fig. 3b, d; Table 1). Higher CR could therefore be expected for spring 2009 due to the higher phytoplankton biomass. Indeed, the mean value of averaged CR over $Z_E$ in 2009 was double that of 2010, with mean (±SD) values of 111.7 (±76.3) and 50.7 (±62.9) mg C m$^{-3}$ d$^{-1}$, respectively (Table 1; $p < 0.001$). The mean averaged CR value in 2009 was comparable to the high rate (i.e. 114 mg C m$^{-3}$ d$^{-1}$) observed during peak planktonic growth in the ECS in summer (Chen et al., 2009). This finding indicates that a huge amount of organic carbon was respired by plankton communities in the spring of 2009.
The CR contour demonstrates spatial patterns of biotic organic consumption across the entire shelf of the ECS. The CR in the surface waters ranged from 10.1 to 458.6 mg C m$^{-3}$ d$^{-1}$ with a mean (± SD) value of 132.0 (±95.6) mg C m$^{-3}$ d$^{-1}$ in 2009 (Fig. 7a). Spatially, in 2009, the higher CR values were mostly along the coast, and surprisingly, in part of the outer shelf of the ECS (e.g. Sts. 9, 10, and 12). The higher CR can be attributed to the higher planktonic biomass; a positive correspondence between CR and phytoplankton biomass or primary production has been observed widely in marine ecosystems (e.g. Jensen et al., 1990; Robinson et al., 2002; Smith and Kemp, 1995). A linear relationship was also apparent between CR and Chl $a$ either in surface waters ($r^2 = 0.34; p < 0.001$) or using averaged values over $Z_E$ ($r^2 = 0.25; p < 0.01$) in this period. The result still holds true when using Chl $a$ expressed in carbon units. Further, phytoplankton respiration was estimated using a biomass specific rate of respiration of 0.25 (Geider, 1992). Results show that all the CR in the spring of 2009, 23.3% was contributed by phytoplankton.

Among other plankton communities, bacterioplankton has been recognized as an important component of organic carbon consumption in many aquatic ecosystems (e.g. Chin-Leo and Benner, 1992; del Giorgio and Duarte, 2002; Griffith et al., 1990). Shiah et al. (2000b) estimated that in the ECS, heterotrophic bacterioplankton has completely consumed in situ particulate organic carbon production. Unfortunately, this component was not measured in the present study. However, to examine how CR relates to plankton communities, POC can be assumed to be an indicator of total planktonic biomass. The averaged POC value over $Z_E$ was in the range of 82.2–613.8 mg C m$^{-3}$, with a mean (± SD) value of 227.5 (±141.9) mg C m$^{-3}$ in 2009 (Table 1). Phytoplankton biomass approximately accounted for 42% of the mean POC, if Chl $a$ was expressed per carbon units. Although the mean Chl $a$ value (1.8 mg Chl m$^{-3}$) in 2009 was not as high as the mean value (3.3 mg Chl m$^{-3}$) observed in summer in previous studies (Table 1; Gong and Liu, 2003; Gong et al., 2003), the POC values in this study were higher than those found in a previous study in summer in the ECS (Chen et al., 2009). Moreover, the high CR rate was linearly regressed with POC both in the surface waters ($r^2 = 0.38; p < 0.001$) and using averaged values over $Z_E$ ($r^2 = 0.31; p < 0.01$) in this period. These results imply that high rates of CR in 2009 were associated with a higher planktonic biomass. The high POC suggested that, in addition to phytoplankton, other plankton communities (e.g. bacterioplankton, protozoan, and zooplankton) might serve as important components contributing to the CR in this period.

### 3.4 Low organic carbon consumption in the spring of 2010

It was reasonable to expect to observe a lower CR in 2010, since the phytoplankton biomass and SST were lower in this period. Indeed, the rates of CR were significantly lower in 2010 compared to those in 2009 ($p < 0.001$; Table 1); the averaged CR values over $Z_E$ ranged from 4.2 to 242.6 mg C m$^{-3}$ d$^{-1}$ with a mean (± SD) value of 50.7 (±62.9) mg C m$^{-3}$ d$^{-1}$ in the spring of 2010 (Table 1). This mean value was at the lower end of the reported CR values in the ECS and in the coastal shelf as well as in the slope regions (i.e. 2.3–485.3 mg C m$^{-3}$ d$^{-1}$ if assuming RQ = 1; Biddanda et al., 1994; Chen et al., 2003, 2006, 2009; Williams, 1984). As stated above, a reason for the lower CR might be the lower phytoplankton biomass observed in this period. This hypothesis can be confirmed in the significant linear relationship found between integrated values over $Z_E$ of CR and Chl $a$ in 2010 (data not shown; $r^2 = 0.29; p < 0.01$), but not that of the surface waters and in the averaged values over $Z_E$.
were five stations with a $P/R$ ratio $\geq 1$ (mean value $= 1.47$), and these stations (Sts. 5, 21, 29, and 30) were mostly in the inner shelf (isobath $\leq 60$ m; Fig. 1; Beardsley et al., 1985), except for St. 28. Interestingly, the lower $P/R$ ratios ($< 1$) were observed mostly in the middle (isobath within 60–100 m) to outer shelves (isobath $> 100$ m) in this period, except for St. 19A. These results suggest that, in the ECS in spring 2010, the inner shelf ecosystem was autotrophic, but the middle to outer shelves were more heterotrophic. Previous studies have also shown that the ECS shelf was a net heterotrophic ecosystem in other seasons (Chen et al., 2003, 2006), except for the inner shelf with high primary productivity ($> 3500$ mg C m$^{-2}$ d$^{-1}$). To support the claim that the ECS is net heterotrophic, high bacterial consumption has been suggested and supported by the observation of a tremendous amount of organic carbon discharged from coastal rivers, especially the Changjiang River (Cauwet and Mackenzie, 1993; Chen et al., 2003; Chen and Wang, 1996). However, high CR was not observed during the high riverine discharge period of 2010 (Table 1; Fig. 2c, d).

Bacterial activity might be limited by lower water temperature (mean value $= 12.2$ °C in the CDW region), even with an enormous amount of organic carbon in the inner shelf. This can further explain why an autotrophic ecosystem was still found in this low primary production region. The low $P/R$ ratio (i.e. 0.85) in this period was also consistent with previous studies, in which such a low ratio (i.e. $< 1$) has been widely observed in coastal regions with low primary productivity (e.g. del Giorgio et al., 1997; Duarte and Agustí, 1998).

### 3.5 Effect of plankton community respiration on $f$CO$_2$

To further understand how organic carbon consumption affects $f$CO$_2$ dissolved in the surface waters, the relationship between CR and $f$CO$_2$ was evaluated. In this study, $f$CO$_2$ was in the range of 130.9–363.4 µatm (mean ± SD = 269.6 ± 55.3 µatm) and 199.7–400.3 µatm (mean ± SD = 293.6 ± 58.4 µatm) in the spring of 2009 and 2010, respectively (Table 1). The mean value of $f$CO$_2$ was slightly higher in 2010 than in 2009, even though the SST was higher in 2009 (Table 1). Exploring the absorption of atmospheric CO$_2$ by surface waters in the ECS, Tsunogai et al. (1999) found that $f$CO$_2$ was positively multiple linear regressed with SST, SSS, and phosphate. Similar multiple regression was also significantly proven for 2009 ($r^2 = 0.74$; $p < 0.001$); however, a significant relationship was not found for 2010. These results indicate that to estimate $f$CO$_2$, the empirical function suggested by Tsunogai et al. (1999) might need to be modified, especially during the cold period in the ECS. Furthermore, $f$CO$_2$ is temperature dependent and should decrease with decreasing temperature (e.g. Goyet et al., 1993; Tsunogai et al., 1999). The mean value of $f$CO$_2$, however, was higher in the lower SST of 2010 than that in the higher SST of 2009 (Table 1). This result suggests that the lower $f$CO$_2$ observed in 2009 might have resulted from...
strong absorption by photosynthesis. Although primary production was not measured in 2009, this assumption could still be indirectly evaluated from relationships between $f$CO$_2$ and Chl $a$, POC, or CR – particularly CR, which is an integrated response of planktonic activities. To verify this, it was found that $f$CO$_2$ was indeed negatively linearly regressed against CR in the surface waters in 2009 ($p < 0.05$; Fig. 8a). A similar relationship still held true between $f$CO$_2$ and the averaged CR over $Z_E$ in 2009 ($p < 0.01$). The higher CR indicates that planktonic activities were vigorous. The lower $f$CO$_2$ observed in 2009 implies that more CO$_2$ was absorbed via photosynthesis than that regenerated from CR in regions with higher planktonic activities, and this could also explain the huge deficiency observed between surface water $f$CO$_2$ (269.6 µatm) in 2009 and atmospheric CO$_2$ (approx. 360 µatm). This implication is supported by the negatively linear relationship found between $f$CO$_2$ and POC in the surface waters of 2009 ($r^2 = 0.43; p < 0.001$). In addition, surface water $f$CO$_2$ might also be affected by a significant amount of freshwater discharge into the ECS. To evaluate, the conservative mixing of TA and DIC data between freshwater and seawater end-members were applied. The TA and DIC data reported by Zhai et al. (2007) for the Changjiang River in spring was used as the freshwater end-member data point (both TA and DIC = 1575 µmol kg$^{-1}$), whereas the averaged surface data at Sts. 10, 12, 24 and 26 in the spring of 2009 were chosen to represent the seawater end-member ($SSS = 34.4$, TA = 2279 µmol kg$^{-1}$, and DIC = 1960 µmol kg$^{-1}$; W. C. Chou, unpublished data). The result shows that $f$CO$_2$ varies from 262 to 277 µatm within a salinity range between 20 and 34.4, which is relatively small compared to the observed inter-annual variation of $f$CO$_2$. It also implies that the effect of the Changjiang River discharge on $f$CO$_2$ in the ECS might be minor in the spring. In addition, these results suggest that there was a strong carbon sink during this study period, especially due to biological uptake.

There was no significant relationship observed between $f$CO$_2$ and CR or Chl $a$ in surface water for 2010 (Fig. 8a). Further, the $f$CO$_2$ was regressed against net community production (NCP), i.e. PP–CR, estimated from measured values since the $f$CO$_2$ should be more directly related to NCP. As expected, a negatively linear relationship was significantly evident between $f$CO$_2$ and NCP in 2010 ($r^2 = 0.42; p < 0.001$; Fig. 8b). This relationship, however, became statistically insignificant if two smaller NCP data points, observed from St. 19A, were excluded from this analysis. These results also imply that effect of biological activity on $f$CO$_2$ might be trivial, especially during a cold period with low primary production. The $f$CO$_2$ might therefore have been driven mostly by the physical properties (e.g. temperature) of seawater during this period. This can further explain why a heterotrophic ecosystem with a low P/R ratio (0.85) would still have a small mean value of $f$CO$_2$ (293.6 µatm). Overall, these results suggest that the relative contribution of planktonic activities and physical processes to shelf carbon cycling in spring might depend on the magnitude of planktonic growth. That is, planktonic communities could have a significant impact on surface water $f$CO$_2$ during flourishing planktonic growth. However, surface water $f$CO$_2$ might be mostly controlled by physical factor(s) and less influenced by planktonic activities in a cold spring period.

4 Conclusions

Previous studies on plankton community respiration (CR) in the East China Sea (ECS) have mostly been conducted in summer, and the rate of CR is significantly correlated with the fluvial discharge rate (e.g. Chen et al., 2009). To fill the seasonal gap, the present study on organic carbon consumption (CR) was performed in the spring of 2009 and 2010, with stations covering almost the entire ECS shelf, when riverine flows were similar to those in summer, with high flu-
Fig. 8. Relationships between fugacity of CO$_2$ (f CO$_2$) vs. (a) plankton community respiration (CR) in the surface waters and (b) net community production (NCP = PP–CR) in the spring of 2009 (●; dashed line) and 2010 (○; solid line). Primary production was used the measured values where incubation performed. Both $p$ and $r^2$ values of linear regression are also shown if statistical significance was evident.
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