Hypoxic Bottom Waters as a Carbon Source to Atmosphere During a Typhoon Passage Over the East China Sea

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Abstract A high-resolution mooring record from the Changjiang River plume (45-m depth) is used to investigate how air-sea CO₂ flux responds to typhoon in the productive plume. With strong wind, surface partial pressure of carbon dioxide (pCO₂) increased sharply from 369 to 606 μatm due to entrainment of high-CO₂ subsurface water. Though it was followed by pCO₂ decrease of 250 μatm and Chl a increase days after the typhoon, the typhoon caused a net CO₂ efflux overall. The maximum CO₂ efflux (+111.6 mmol·m⁻²·day⁻¹) is much greater than that under non-typhoon condition (−2.3 to −11.7 mmol·m⁻²·day⁻¹). Based on historical typhoon records, we estimate typhoon-induced CO₂ efflux to be +0.27 Tg C/year, which can cancel 18% of summer CO₂ influx in the East China Sea shelf. It may likely occur in other coastal waters. Ignoring such contribution may induce large bias in estimating regional air-sea CO₂ flux.

Plain Language Summary Air-sea CO₂ flux estimations in shelf waters are improving in recent decades but still have large uncertainties. Short-term events, such as tropical cyclones, could have significant influences in air-sea CO₂ flux estimations. In addition, recent climate models suggest tropical cyclones may become more intense over the coming century. We know little about how they influence regional air-sea CO₂ flux. Here, we present a high-resolution mooring record from the Changjiang River plume to investigate how air-sea CO₂ flux responds to typhoon. In our record, surface partial pressure of carbon dioxide (pCO₂) increased sharply from 369 to 606 μatm due to entrainment of high-CO₂ subsurface water. Though it was followed by pCO₂ decrease and Chl a increase days after the typhoon, the typhoon caused a net CO₂ efflux overall. The typhoon transferred CO₂ from surface waters to atmosphere at a maximum rate of 111.6 mmol·m⁻²·day⁻¹. Based on historical typhoon records, we estimate typhoon-induced CO₂ efflux to be +0.27 Tg C/year, which can cancel out 18% of summer CO₂ influx in the East China Sea shelf. It may likely occur in other coastal waters. Ignoring such contribution may induce large bias in estimating regional air-sea CO₂ flux.

1. Introduction

Despite constituting only 7% of the global ocean surface area, shelf seas account for 14–30% of the global primary production, 80% of the organic matter burial, and 50% of the calcium carbonate deposition (Gattuso et al., 1998); they are an important component of the global carbon cycling. Previous studies suggested that shelf waters are an important sink of atmospheric CO₂, taking up CO₂ at a rate of 0.21–0.45 Pg C/year (F = 1 × 10⁻¹⁰; Borges et al., 2005; Cai et al., 2006; Chen et al., 2013; Laruelle et al., 2018). A large fraction of carbon absorbed from the atmosphere is respired in subsurface waters, which releases CO₂ into the water column (Cai et al., 2011; Chou et al., 2009). Thus, to maintain the net carbon sink of shelf seas, CO₂-undersaturated surface layer and CO₂-rich subsurface water should be separated (Chou et al., 2009; Thomas et al., 2004).

However, episodic events such as tropical cyclones (we use typhoons thereafter as our study area is the East China Sea shelf) can well mix the water column and cause significant CO₂ efflux in coastal waters within days (Crosswell et al., 2014; Huang & Imberger, 2010; Nemoto et al., 2009). Note that we will likely have more intense typhoons in a warmer future according to climate models (Webster et al., 2005). In shelf seas, CO₂ efflux during a typhoon is usually much higher than that of normal weather due to combined effect of
mixing or upwelling of subsurface water with high dissolved inorganic carbon (DIC; Mathis et al., 2012; Ye et al., 2017) and extreme wind speed (Huang & Imberger, 2010; Nemoto et al., 2009).

Such influence can be amplified when bottom shelf waters are hypoxic and enriched with CO₂ (Cai et al., 2011; Rabalais et al., 2014; Xue et al., 2015; Yu et al., 2014). Surface pCO₂ in the hypoxic inner East China Sea shelf is predicted to increase by 312 μatm after vertical mixing based on model simulation (Chou et al., 2009), which is much higher than that observed in the South China Sea shelf (increase by 20 μatm; Ye et al., 2017). Field observations in the Neuse River Estuary showed that intense mixing can trigger intense carbon efflux of +4.080 mmol C·m⁻²·day⁻¹ in shallow bottom hypoxic waters (+2.4 mmol C·m⁻²·day⁻¹ before typhoon; Crosswell et al., 2014). In spite of this, observations of pCO₂ variation and air-sea CO₂ flux during typhoons in the hypoxic shelf are still scarce.

The inner East China Sea shelf is an ideal place to study how typhoon influences air-sea CO₂ flux in hypoxic shelf waters. It represents one of the most studied eutrophic coastal waters and is also a typical sink of atmospheric CO₂ in summer (Guo et al., 2015; Tseng et al., 2014; Tsunogai et al., 1999; Zhai & Dai, 2009). Due to respiration of sinking organic carbon, increasing DIC and large-area hypoxia has been frequently observed in bottom waters (Wang, Chen, Jin, et al., 2017; Wang et al., 2016). CO₂-undersaturated upper layer and carbon-rich subsurface waters are separated by strong stratification in summer (Ni et al., 2016; Wang, Chen, Jin, et al., 2017; Zhai & Dai, 2009). A previous study reported large CO₂ efflux triggered by wind mixing in early autumn, which weakened stratification of the water column (Li et al., 2018). It is likely that carbon-rich subsurface waters in the inner East China Sea could also have significant impact on air-sea CO₂ flux in summer, considering that more than five typhoons visit this shelf each year.

In this study, we use time series of buoy data to evaluate how surface pCO₂ and air-sea CO₂ flux respond to vertical mixing in the inner East China Sea shelf and biological processes afterward. To the best of our knowledge, no high-resolution time series observations of pCO₂ variation during typhoon passage in the inner East China Sea shelf have ever been reported. In addition, we calculate annual air-sea CO₂ flux induced by typhoons in the whole East China Sea shelf, based on 22-year historical typhoon track record.

2. Materials and Method

2.1. Buoy Deployment and Sample Measurements

Typhoon Chan-hom in 2015 is a Category-2 typhoon with wind velocity higher than 40 m/s. It entered the East China Sea on 7 July and left on 14 July. The variations of sea surface pCO₂ before, during, and after the typhoon were obtained using a moored buoy (3–20 July). It was deployed at a Changjiang River plume site, which was located on the typhoon track (water depth ~45 m, 122.8°E, 30.6°N, supporting information Figure S1). Details of buoy observations were presented in Li et al. (2018) and Wang, Chen, Jin, et al. (2017). Our buoy also measured sea surface salinity, sea surface temperature (SST), surface dissolved oxygen (DO), surface chlorophyll a (Chl a), and 2-m wind. As our buoy wind direction data were not good enough, we also collected wind direction from National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis 10-m wind data (124°E, 31.3°N). In addition, bottom water temperature was measured. All sensors collected data every 15 min, except for pCO₂ which was measured at 30-min intervals. Details of instruments deployed are presented in the supporting information Text S1.

A Multi Water Sampler (Hydro-Bios) was used to collect discrete water samples in August 2013. In August 2017, water samples were collected with 5-L Niskin bottles mounted on a rosette assembly. Temperature and salinity were recorded using a Seabird SBE 917 profiler. DIC and total alkalinity (TA) samples were collected, stored, and measured according to Cai et al. (2004). The precisions of the DIC and TA analyses were both ±2 μmol/kg. Certified reference materials from A.G. Dickson (Scripps Institution of Oceanography) were used to calibrate the analyses results. Discrete pCO₂ value of stations are calculated using the program CO2SYS based on the inputs of DIC, TA, salinity, and temperature (Pierrot et al., 2006). DO was determined using the Winkler titration method. Chl a samples were measured with a 10-AU Field Fluorometer (Turner Designs) after extraction with 90% acetone.
2.2. Satellite-Retrieved SST
We collected remote sensing SST data 2 days before and after the typhoon in the East China Sea from Remote Sensing System (http://www.remss.com/). The SSTs are Microwave Optimally Interpolated daily SST product with 9-km resolution. It combines the through-cloud capabilities of the microwave data with the high-spatial-resolution and near-coastal capability of the infrared SST data. SSTs before and after 115 typhoons passing the East China Sea from 1998–2018 were collected. The sea surface coolings by typhoon mixing were evaluated by calculating ΔSST (posttyphoon SST minus SST before typhoon).

2.3. Typhoon-Induced Air-Sea Carbon Flux
Air-sea CO2 flux is estimated using $F_{gas} = k \times s \times \Delta pCO2$ where $k$ is the gas transfer velocity, $s$ is carbon dioxide solubility (Weiss, 1974), and $\Delta pCO2$ is the difference between sea surface $pCO2$ and air $pCO2$, which is assumed to be a constant of 396 μatm (calculated from monthly air $pCO2$ in July 2015 at Korea’s Taean Peninsula site, ftp://aftp.cmdl.noaa.gov). The gas transfer velocity (cm/hr) is calculated according to Wanninkhof (2014).

We also estimate annual typhoon-induced air-sea carbon flux in the East China Sea. Total efflux of a single typhoon can be estimated as follows: total efflux (g C) = daily flux (mmol·m^{-2}·day^{-1}) × area (m²) × duration (day) × 12 g/mol. Daily flux can be estimated using $F_{gas} = k \times s \times \Delta pCO2$. First, we categorize the East China Sea shelf into inner shelf and outer shelf, as $\Delta pCO2$ and air-sea fluxes induced by typhoons have sharp differences between the two regions. The reasons for such large differences are explained in section 3.2. We set $\Delta pCO2 = 200$ μatm in the inner shelf and $\Delta pCO2 = 14$ μatm in the outer shelf for every typhoon passage. Details of $\Delta pCO2$ chosen can be seen in the supporting information.

Because typhoon wind speed decreases from typhoon core to typhoon periphery, we decide not to use a single wind speed for a particular typhoon. In this study, we adopt a wind speed gradient: maximum wind speed from typhoon core to typhoon periphery, we decide not to use a single wind speed for a particular typhoon. In this study, we adopt a wind speed gradient: maximum wind speed, 25.7 m/s (50 knot wind), 1 knot = 0.514 m/s) and 15.4 m/s (30 knots; supporting information Table S1). Each wind speed covers a specific influenced area which can be calculated by typhoon radius ($R_{30}$ or $R_{50}$, typhoon radius with 30- or 50-knot wind). The details of area calculation can be seen in the supporting information Text S1.

3. Results and Discussion
Our 18-day mooring records showed large fluctuations of $pCO2$, from pretyphoon to posttyphoon period. Prior to the typhoon, the inner shelf was under strong northerly wind (maximum wind velocity > 11.5 m/s) on 7 July, which triggered strong vertical mixing already. We define the period of 3–7 July as Period I. Discussion of the effect of vertical mixing on $pCO2$ is mainly based on the data in Period I (Figure 1). The typhoon passed our buoy during Period II (7–13 July). Period III (13–20 July) covers the time when the typhoon wind ceased and stratification was formed. As we focus on daily variation, high-frequency $pCO2$, DO, and Chl a data are firstly averaged into daily data.

3.1. Large Surface $pCO2$ Variation During Typhoon Passage: Vertical Mixing and Biological Production
At the beginning of Period I (4–7 July), there was strong northerly wind (maximum wind velocity > 11.5 m/s). SST decreased by 1.32 °C (to 20.53 °C) within 3 days (4 to 7 July) whenbottom temperature increased by 1.05 °C (to 20.65 °C, Figure 1b). Surface DO decreased by 35 μmol/L. Meanwhile, surface $pCO2$ increased from 369 to 606 μatm (Figure 1c). Such $pCO2$ increase (237 μatm) is similar to that predicted by Chou et al. (2009; 242 μatm) but much higher than that reported in the South China Sea (20 μatm; Ye et al., 2017).

Large surface $pCO2$ variation has been frequently observed in the shelf, which results from multiple processes: mixing and advection of water mass, biological activity, temperature variation, air-sea CO2 exchange, etc. (DeGrandpre et al., 1998; Li et al., 2018). Surface temperature and bottom temperature approached each other (4 to 7 July, Figure 1b), indicating the mixed layer had deepened due to strong vertical turbulent mixing. Similar observation was reported by Nemoto et al. (2009) in the outer East China Sea shelf. Variations of $T/S$ (temperature/salinity) characteristic of surface waters during Period I also suggest entrainment of cold
subsurface water (Figure 2a). Such entrainment can explain the $p_{CO_2}$ increase and DO decrease during Period I. Although we do not have subsurface samples before this vertical mixing event, vertical profiles in our past cruises always showed high $p_{CO_2}$ and low oxygen in the subsurface water near our buoy site (Figure 2b). High-$p_{CO_2}$ subsurface water has also been observed frequently in the inner shelf by other studies, due to intense respiration of organic matter (Chou et al., 2009; Wang, Chen, Jin, et al., 2017). The concurrent occurrences of vertical mixing and $p_{CO_2}$ increase suggest that $p_{CO_2}$ variation during Period I was probably controlled by entrainment of high-$p_{CO_2}$ subsurface water. The dominant effect of vertical mixing or upwelling of DIC-enriched subsurface water on surface $p_{CO_2}$ has also been observed in the East China Sea shelf (Li et al., 2018) and other coastal waters (Kortzinger et al., 1997; Mathis et al., 2012), which are opposite to that in the open ocean, where surface cooling controls $p_{CO_2}$ during tropical cyclone passage (decrease $p_{CO_2}$ by ~20–40 $\mu$atm; Bates et al., 1998; Huang & Imberger, 2010).
In the shallow coastal waters, stirring of sediment pore water DIC and in situ respiration of organic matter during typhoon may also be important in influencing pCO2 (Crosswell et al., 2014). In this study, the sharp pCO2 increase was probably dominated by vertical mixing of the two water masses, not by in situ respiration, as indicated by the significant negative relationship between pCO2 and temperature (Figure 2c). We can quantify pCO2 increase due to mixing in the inner shelf. If we assume a thoroughly mixed water column of Stations 18–21 and 29 in Chou et al. (2009; the inner shelf), the DIC of surface waters will increase (ΔDIC) by 93–196 μmol/kg (using the trapezoidal rule). Using the Revelle Factor (RF) = 10 (Zhai & Dai, 2009), pCO2 increase (ΔpCO2) can be calculated by ΔpCO2 ≈ ΔDIC/DIC × RF × pCO2 = 124–295 μatm.

In contrast, most studies suggested biological activity consumes DIC and decreases pCO2 in the surface waters of the East China Sea shelf (Tseng et al., 2014; Zhai & Dai, 2009). Net production of DIC is generally reported in the subsurface water (Chou et al., 2009). If we adopt net community production of 30–64 mg·m\(^{-3}\)·day\(^{-1}\) in the water column, as reported in Chen et al. (2003), DIC increase will be 7.8–15.6 μmol/kg assuming seawater density of 1.024 kg/m\(^3\) and duration of 3 days. It is an order magnitude smaller than that of vertical mixing.

The typhoon traveled to our buoy site on 11 July; pCO2 peaked during the following 2 days (576 to 602 μatm, Period II). It was probably because vertical mixing during 4–7 July had mixed the water column thoroughly (Figure 1b). From 7 to 9 July, advection of less saline water decreased the salinity by 2.4. We did not observe sharp pCO2 variation similar to that during Period I. It can be explained as the horizontal gradient of pCO2 was much smaller than that of the vertical pCO2 gradient. In addition, vertical mixing also reduced the horizontal gradient of pCO2.

On 13 July, 2 days after the typhoon, relaxation of wind and increasing surface temperature favored the formation of stratification (Figures 1b and 1f). For the following 6 days (13–19 July, Period III), daily pCO2 decreased by 230 μatm (from 602 μatm, Figure 1c). Supersaturated DO and increasing Chl a were both observed, while daily salinity stayed relatively constant in the coastal waters (26.25–27.27, Figures 1a, 1d, 2a).
and 2a), suggesting strong influence of biological production. In addition to the mooring record, our cruise data on 17 July also showed high Chl a at the surface (3.61 μg/L), and even at 30 m (2.60 μg/L; supporting information Figure S3). Increased Chl a several days after the typhoon has been previously reported in the East China Sea shelf (Hung et al., 2010), South China Sea (Lin et al., 2003), and Gulf of Mexico (Shi & Wang, 2007). Furthermore, we observed significant relationship between pCO2 and Chl a with a slope value of −34.49 (supporting information Figure S2), which is close to that obtained using underway data in the East China Sea shelf (−49.8; Tseng et al., 2014). Very significant relationship between pCO2 and DO was also observed (Figure 2c), which was similar to previous studies (Li et al., 2018; Zhai & Dai, 2009). Such significant relationships suggest the controlling effect of biological production on surface pCO2 during Period III. Biological activity after the typhoon could be related to nutrient supplies from vertical mixing (Hung et al., 2010; Shi & Wang, 2007) or rainfall. Heavy precipitations after a typhoon can carry terrestrial nutrients into coastal waters by river discharge (Meng et al., 2017), besides direct wet deposition. However, their effects on air-sea carbon flux are largely unknown. Intensive biological activity after the typhoon likely links to bottom hypoxia, as previous observations showed that DO of bottom water under the Changjiang River plume decreased by 109–137 μmol/L 1–2 weeks after wind mixing events (Ni et al., 2016; Wang, Chen, Jin, et al., 2017).

### 3.2. Hypoxic Subsurface Water as a Potential CO2 Source to the Atmosphere

The maximum daily average air-sea CO2 flux during vertical mixing was +111.6 mmol·m⁻²·day⁻¹ using the gas transfer velocity parameterization of Wanninkhof (2014; Figure 1e), which is much greater than that under nontyphoon condition and in reverse direction (air to sea, −2.3 to −11.7 mmol·m⁻²·day⁻¹ in four seasons; Guo et al., 2015; Zhai & Dai, 2009). Biological production several days after the typhoon decreased pCO2 significantly and made the buoy site a weak carbon sink (−0.5 mmol·m⁻²·day⁻¹; Figure 1e). However, the buoy site was still a strong source of atmospheric carbon if the whole typhoon period (11–20 July) was considered (Figure 1e). Large-scale biological bloom triggered by along-shore plume extension was observed 2–3 weeks after typhoon Chan-hom (Zhang et al., 2018). It can possibly reduce the typhoon-induced CO2 efflux. Unfortunately, the effect of such posttyphoon phenomenon on typhoon-induced air-sea carbon flux is difficult to be evaluated quantitatively. Recent studies showed that gas transfer velocity could vary significantly during strong wind due to bubble-mediated gas exchange (Prytherch et al., 2010). If using the expression of Prytherch et al. (2010), which spans a larger range of wind speed, the daily efflux could be up to +258.4 mmol·m⁻²·day⁻¹ (Figure 1e). It should be significant in influencing regional air-sea CO2 estimate in the East China Sea shelf.

We cannot simply apply such extreme carbon efflux to the entire shelf. Typhoon-induced carbon efflux in the inner East China Sea shelf (+111.6 mmol·m⁻²·day⁻¹) in this study is higher than that in Wu (2015; +48.8 mmol·m⁻²·day⁻¹) and in Nemoto et al. (2009; +21.2 mmol·m⁻²·day⁻¹) in the outer shelf (supporting information Table S2), though typhoon wind speed in this study is lower than that in both of those studies. The increasing trend of carbon efflux per typhoon from the outer shelf to the inner shelf indicates complex spatial variation of carbon efflux during a typhoon. It can be explained as ΔpCO2 (sea pCO2 − air pCO2) after vertical mixing in hypoxic waters of the inner shelf (192–207 μatm) is much higher than that in the outer shelf (13–48 μatm; Figure 3d and supporting information Table S2). Such extremely high ΔpCO2 after a typhoon is probably related to bottom hypoxia in the inner shelf.

As explained in section 3.1, increasing sea surface pCO2 in the inner East China Sea shelf during wind event was caused by mixing of surface waters with carbon-enriched subsurface waters. Extra CO2 is added into the subsurface waters in the inner shelf by enhanced respiration of organic carbon, which consumes oxygen and releases CO2 stoichiometrically (Cai et al., 2011; Wang, Chen, Jin, et al., 2017). Thus, hypoxic waters could have much more DIC when compared with nonhypoxic waters. The hypoxic subsurface waters (in the inner shelf) generally have DIC of ~2,100 μmol/kg, and pCO2 of ~650 μatm (calculated using CO2SYS). In the summer of 2017, we even observed hypoxic waters with oxygen concentration < 20 μmol/kg near our buoy station (123°E, 31°N; personal communication with Yanyi Miao in October, 2017), which is the lowest value ever reported. The calculated pCO2 of the bottom water is 1.022 μatm (Figure 3d), which is more than twice the air pCO2 (396 μatm). In addition, hypoxia and carbon accumulation could be enhanced due to the combined effect of global warming and regional eutrophication (Rabalais et al., 2014; Wang et al., 2016). In
contrast, the bottom waters of the outer shelf showed DIC concentration of ~2,020–2,040 μmol/kg, and $pCO_2$ of ~419–550 (Chou et al., 2009; Wang, Chen, Jin, et al., 2017).

3.3. Extensive CO2 Efflux During Typhoon Passage

Remote sensing ΔSST (post-typhoon SST – SST before typhoon) during Typhoons Chan-hom in 2015 (a), Rumbia in 2018 (b), and Bolaven in 2012 (c); Δ$pCO_2$ (sea $pCO_2$ – air $pCO_2$) and air-sea carbon fluxes during six typhoons in the inner and outer shelves (d); statistic analysis of ΔSST during typhoons from 1998 to 2018 (e); annual typhoon-induced carbon efflux from 1997 to 2018 (f). In d, flux data were obtained from our study, Nemoto et al. (2009), and Wu (2015). The dash box and grey shade denote the area of the inner shelf and outer shelf in estimation, respectively. Bottom $pCO_2$ in the inner shelf (cruise in 2017) and outer shelf (cruise in 2007, obtained from Chou et al., 2009) are also shown. The blue dash line shows the 200-m isobath. In e, the lowest ΔSST for every typhoon was chosen for analysis. In f, red dash line and blue dash line are the annual-averaged-typhoon-induced carbon efflux for the whole shelf and average carbon efflux under non-typhoon condition (obtained from Tseng et al., 2014), respectively. SST = sea surface temperature.

Figure 3. Annual typhoon-induced carbon efflux in the East China Sea shelf. ΔSST (post-typhoon SST – SST before typhoon) during Typhoons Chan-hom in 2015 (a), Rumbia in 2018 (b), and Bolaven in 2012 (c); Δ$pCO_2$ (sea $pCO_2$ – air $pCO_2$) and air-sea carbon fluxes during six typhoons in the inner and outer shelves (d); statistic analysis of ΔSST during typhoons from 1998 to 2018 (e); annual typhoon-induced carbon efflux from 1997 to 2018 (f). In d, flux data were obtained from our study, Nemoto et al. (2009), and Wu (2015). The dash box and grey shade denote the area of the inner shelf and outer shelf in estimation, respectively. Bottom $pCO_2$ in the inner shelf (cruise in 2017) and outer shelf (cruise in 2007, obtained from Chou et al., 2009) are also shown. The blue dash line shows the 200-m isobath. In e, the lowest ΔSST for every typhoon was chosen for analysis. In f, red dash line and blue dash line are the annual-averaged-typhoon-induced carbon efflux for the whole shelf and average carbon efflux under non-typhoon condition (obtained from Tseng et al., 2014), respectively. SST = sea surface temperature.

3.3. Extensive CO2 Efflux During Typhoon Passage

Remote sensing ΔSST (post-typhoon SST minus SST before typhoon) results showed that typhoons Chan-hom (2015), Rumbia (2018), and Bolaven (2012) induced large cold patches along their tracks in the East China Sea shelf (Figures 3a, 3b and 3c). In addition, large carbon effuxes were observed during the passage of the three typhoons (supporting information Table S1). Statistical analysis of 115 typhoons during past 20 years also showed that the SST of 52% typhoons decreased by 2 to 4 °C, indicating that subsurface waters were brought to the surface by typhoon passage in the shelf (Figure 3e).

Here, we estimate CO2 efflux contributed by typhoon in the inner and outer East China Sea shelves. The boundary of the inner shelf (shallower than 50 m) is defined based on the historical hypoxia area of Wei et al. (2017) and the inner shelf boundary of Guo et al. (2015; Figure 3d). The calculation method is presented in section 2.3. Briefly, total efflux of a single typhoon can be estimated as follows: carbon efflux (g C) = daily flux (mmol·m−2·day−1) × duration (day) × area (m2) × 12 g/mol. In air-sea CO2 flux estimate, we use Δ$pCO_2$ of +200 μatm (in this study) for the inner shelf and +14 μatm for the outer shelf (Nemoto et al., 2009; supporting information Table S2). Wind speed, duration, and area data are calculated based on the Japan Meteorological Agency best track data.

The calculated annual average typhoon-induced CO2 efflux (averaged during 1997–2018) is +0.27 Tg (1 Tg = 1 × 1012 g; Figure 3f), using the gas transfer velocity of Wanninkhof (2014). It can cancel out 18% of the summer influx in the shelf (~1.48 Tg, area of 453 × 105 km2; Tseng et al., 2014; Figure 3f). Our results suggest that the air-sea carbon flux induced by typhoons could likely weaken the carbon sink of the East China Sea shelf in summer. In previous studies, typhoons were reported to enhance carbon efflux (Bates et al., 1998; Nemoto...
et al., 2009). Carbon efflux contributed by typhoon in the western subtropical North Pacific accounts for 69–96% of the summer carbon efflux (Nemoto et al., 2009).

Such estimate still contains large uncertainties. First, $\Delta$pCO$_2$ could have large variation due to different preconditions of ocean before typhoon, especially in the inner shelf. CO$_2$ in subsurface waters increases continuously during the development of hypoxia. Also, the string of sediment during strong winds could release DIC of pore water into the water column (Crosswell et al., 2014). Second, according to Hung et al. (2010), responses of Chl a and particulate carbon flux to typhoons could be distinct in the East China Sea. Though the role of posttyphoon phytoplankton blooms in influencing air-sea carbon flux is minor when compared to that of vertical mixing in our study, they can possibly reduce the effects of typhoons on releasing the CO$_2$ out of the ocean during other typhoon events or even enhance the carbon sink of the East China Sea shelf. Third, typhoon-induced rainfall brings massive terrestrial matter into coastal waters (Dadson et al., 2005; He et al., 2014). We still do not much about respiration of such terrestrial organic carbon in the water column and the nutrient transports and whether they influence air-sea carbon efflux. Fourth, the relationship between gas transfer velocity and wind has large uncertainty as gas transfer velocity data during strong winds are still very scarce (Crosswell et al., 2014; Prytherch et al., 2010).

Such multiple processes and factors call more field observations of carbon system during typhoon events. And a combination of high-frequency mooring observations, remote sensing observations, numerical models, and ship-based observations is needed to produce accurate and precise typhoon-induced air-sea CO$_2$ flux estimates. Notwithstanding, our observation data in the inner shelf provide an opportunity to assess typhoon-induced air-sea CO$_2$ flux in the East China Sea. Strong efflux due to entrainment of high pCO$_2$ subsurface water suggested that subsurface DIC was a significant potential source of atmospheric carbon in the East China Sea shelf. It may likely occur in other coastal waters. There will be large biases in regional air-sea CO$_2$ flux if such potential sources are ignored in estimation.

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Kortzinger, A., Duinker, J. C., & Mintrop, I. (1997). Strong CO₂ emissions from the Arabian Sea during the southwest monsoon. Geophysical Research Letters, 24(14), 1763–1766. https://doi.org/10.1029/97GL01775

Laruelle, G. G., Cai, W.-J., Hu, X. P., Gruber, N., Mackenzie, F. T., & Regnier, P. (2018). Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide. Nature Communications, 9(1), 454. https://doi.org/10.1038/s41467-017-02738-z

Li, D. W., Chen, J. F., Ni, X. B., Wang, K., Zeng, D. Y., Wang, B., et al. (2018). Effects of biological production and vertical mixing on sea surface pCO₂ variations in the Changjiang River plume during early autumn: A buoy-based time series study. Journal of Geophysical Research: Oceans, 123(9), 6156–6173. https://doi.org/10.1029/2017JC013740

Lin, J., Liu, W. T., Wu, C. C., Wong, G. T., Hu, C., Chen, Z., et al. (2003). New evidence for enhanced ocean primary production triggered by tropical cyclone. Geophysical Research Letters, 30(13), 1718. https://doi.org/10.1029/2003gl017141

Mathis, J. T., Pickart, R. S., Byrne, R. H., Mcneil, C., Moore, G. W. K., Juranek, L. W., et al. (2012). Storm-induced upwelling of high pCO₂ waters onto the continental shelf of the western Arctic Ocean and implications for carbonate mineral saturation states. Geophysical Research Letters, 39, L07060. https://doi.org/10.1029/2012GL051574

Meng, P. J., Tew, K. S., Hsieh, H. Y., & Chen, C. (2017). Relationship between magnitude of phytoplankton blooms and rainfall in a hyper-eutrophic lagoon: A continuous monitoring approach. Marine Pollution Bulletin, 124(2), 897–902. https://doi.org/10.1016/j.marpolbul.2016.12.040

Nemoto, K., Midorikawa, T., Wada, A., Ogawa, K., Takatani, S., Kimoto, H., et al. (2009). Continuous observations of atmospheric and oceanic CO₂ using a moored buoy in the East China Sea: Variations during the passage of typhoons. Deep-Sea Research Part II, 56(8–10), 542–553. https://doi.org/10.1016/j.dsr2.2008.12.015

Ni, X. B., Huang, D. J., Zeng, D. Y., Zhang, T., Li, H. L., & Chen, J. F. (2016). The impact of wind mixing on the variation of bottom dissolved oxygen off the Changjiang Estuary during summer. Journal of Marine System, 154, 122–130. https://doi.org/10.1016/j.jmarsys.2014.11.010

Pierrot, D., E. Lewis, and D. Wallace (2006), MS Excel program developed for CO₂ system calculations. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, ORNL/CDIAC-10S.

Przytych, J., Yelland, M. J., Pascal, R. W., Skjelvan, I., & Srokosz, M. A. (2010). Open ocean gas transfer velocity derived from long-term direct measurements of the CO₂ flux. Geophysical Research Letters, 37, L23607. https://doi.org/10.1029/2010gl043597

Rahbaghi, N. N., Cai, W.-J., Castenssen, J., Conley, D. J., Fry, B., Hu, X., et al. (2014). Eutrophicacean driven deoxygenation in the coastal ocean. Oceanography, 27(1), 172–183. https://doi.org/10.5670/oceanog.2014.21

Shi, W., & Wang, M. H. (2007). Observations of a Hurricane Katrina-induced phytoplankton bloom in the Gulf of Mexico. Geophysical Research Letters, 34, L11607. https://doi.org/10.1029/2007GL029724

Thomas, H., Bozec, Y., Elkalay, K., & De Baar, H. J. W. (2019). Enhanced open ocean storage of CO₂ from shell sea pumping, Science, 364(6457), 1005–1008. https://doi.org/10.1126/science.1095491

Teng, C. M., Shen, P. Y., & Liu, K. K. (2014). Synthesis of observed air-sea CO₂ exchange fluxes in the river-dominated East China Sea and improved estimates of annual and seasonal net mean fluxes. Biogchronicles, 11(4), 3855–3870. https://doi.org/10.5194/bg-11-3855-2014

Tsunogai, S., Watanabe, S., & Sato, T. (1999). Is there a continental shelf pump? Tellus B, 51(3), 701–712. https://doi.org/10.3402/tellusb.v51i3.16468

Wang, B., Chen, J. F., Jin, H. Y., Li, H. L., Huang, D. J., & Cai, W.-J. (2017). Diatom bloom-derived bottom water hypoxia off the Changjiang estuary, with and without typhoon influence. Limnology and Oceanography, 62(4), 1552–1569. https://doi.org/10.1002/lno.10517

Wang, H. J., Dai, M. H., Liu, J. W., Kao, S.-J., Zhang, C., Cai, W.-J., et al. (2016). Eutrophyication-driven hypoxia in the East China Sea off the Changjiang Estuary. Environmental Science & Technology, 50(5), 2255–2263. https://doi.org/10.1021/acs.est.5b06211

Wang, K., Chen, J. F., Ni, X. B., Zeng, D. Y., Li, D. W., Jin, H. Y., et al. (2017). Real-time monitoring of nutrients in the Changjiang Estuary reveals short-term nutrient-algal bloom dynamics. Journal of Geophysical Research: Oceans, 122, 5590–5403. https://doi.org/10.1002/2016JC012450

Wanninkhof, R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. Limnology and Oceanography: Methods, 12(6), 351–362. https://doi.org/10.4319/lom.2014.12.351

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment, Science, 309(5742), 1844–1846. https://doi.org/10.1126/science.1116448

Wei, Q. S., Wang, B. D., Yu, Z., Chen, J. F., & Xue, L. (2017). Mechanisms leading to the frequent occurrences of hypoxia and a preliminary analysis of the associated acidification off the Changjiang estuary in summer. Science China Earth Sciences, 60(2), 360–381. https://doi.org/10.1007/s11430-015-5542-8

Weiss, R. F. (1974). Carbon dioxide in water and seawater: the solubility of a non-ideal gas. Marine Chemistry, 2(3), 203–215. https://doi.org/10.1016/0304-4203(74)90005-2

Wu, Y. X. (2015). pCO₂ on the mid-shelf of the East China Sea, Buoy-based time series observations (in Chinese, master's dissertation) (pp. 1–109). Xiamen: Xiamen University.

Xue, J. H., Cai, W.-J., Hu, X. P., Huang, W.-J., Lohrenz, S. E., & Gudserensen, K. (2015). Temporal variation and stoichiometric ratios of organic matter remineralization in bottom waters of the northern Gulf of Mexico during late spring and summer. Journal of Geophysical Research: Oceans, 120, 8304–8326. https://doi.org/10.1002/2015JC011453

Ye, H. J., Sheng, J. Y., Tong, D. L., Siwanto, E., Kalhorn, M. A., & Sui, Y. (2017). Storm-induced changes in pCO₂ at the sea surface over the northern South China Sea during Typhoon Wutip. Journal of Geophysical Research: Oceans, 122, 4761–4778. https://doi.org/10.1002/2016jo12643

Yu, L., Fennel, K., Laurent, A., Murrell, M. C., & Lehrer, J. C. (2014). Numerical analysis of the primary processes controlling oxygen dynamics on the Louisiana shelf. Biogchronicles, 12(7), 2063–2076. https://doi.org/10.5194/bg-12-2063-2015

Zhai, W. D., & Dai, M. H. (2009). On the seasonal variation of air-sea CO₂ fluxes in the outer Changjiang (Yangtze River) Estuary, East China Sea. Marine Chemistry, 117(1–4), 2–10. https://doi.org/10.1016/j.marchem.2009.02.008

Zhang, Z. H., Wu, H., Yin, X. Q., & Qiao, F. L. (2018). Dynamic response of Changjiang River plume to a severe typhoon with the surface wave-induced mixing. Journal of Geophysical Research: Oceans, 123(12), 9369–9388. https://doi.org/10.1029/2018jc014266

References From the Supporting Information

Takagi, H., & Wu, W. (2015). Maximum wind radius estimated by the 50 kt radius: Improvement of storm surge forecasting over the western North Pacific. Natural Hazards and Earth System Sciences, 15(3), 705–717. https://doi.org/10.5194/nhess-15-705-2016
Erratum

In the originally published version of this article, author Jianfang Chen’s name was incorrect. This error has since been corrected and the present version may be considered the authoritative version of record.