Biogeosciences Discuss., 10, 19867–19893, 2013
www.biogeosciences-discuss.net/10/19867/2013/
doi:10.5194/bgd-10-19867-2013

Biogeosciences
Discussions
Open Access

Impacts of a weather event on shelf circulation and CO_2 and O_2 dynamics on the Louisiana shelf during summer 2009

W.-J. Huang[1,2], W.-J. Cai[2], Y. Wang[1], and C. S. Hopkinson[1]

[1]Department of Marine Sciences, University of Georgia, Athens, Georgia, 30602, USA
[2]College of Earth, Ocean, and Environment, University of Delaware, Newark, Delaware, 19716, USA

Received: 4 November 2013 – Accepted: 4 December 2013 – Published: 17 December 2013

Correspondence to: W.-J. Cai (wcai@udel.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

While much is known about the physics of coastal currents, much less is known about the biogeochemical effects of surface currents on shelf carbon dioxide (CO_2) and oxygen distribution and dynamics. The Mississippi and Atchafalaya River plume is usually observed along the Louisiana shelf with easterly winds. Such a typical pattern was observed in August 2007, i.e. a plume of low salinity and low partial pressure of CO_2 (pCO_2), indicating high biological production on the inner shelf; and higher salinity and pCO_2 on the outer shelf. This high biological production induced by riverine nitrogen flux thus provided major organic matter sources for the shelf-wide hypoxia (dissolved oxygen [DO] $< 2\,\mathrm{mg\,L^{-1}}$) accompanied by high dissolved inorganic carbon (DIC) concentrations in the bottom water. The slope of the DO and DIC relationship also demonstrated Redfield-type respiration in this shelf-wide hypoxia. In contrast, summer 2009 was an abnormal season characterized by a cool temperature in the central North America. Our observation and satellite chlorophyll *a* patterns both displayed a greatly distinct situation, i.e., the river plume was relocated to the eastern part of the Louisiana shelf; and high salinity and high pCO_2 values occurred in surface waters of the western inner shelf. This plume relocation shifted the Louisiana shelf from a normally weak CO_2 sink (as in 2007) to a strong CO_2 source for the atmosphere. Although riverine nitrogen flux was enough to support a shelf-wide hypoxia in 2009, the plume relocation changed the location of high biological production and resulted in a limited hypoxic area. Furthermore, DIC concentration in bottom waters was higher than those predicted by the Redfield ratio, most likely because of much rapid O_2 compensation than CO_2 loss during air–sea exchange. Numerical models indicate such relocation of plume was mostly affected by the shelf circulation dominated by southerly and southwesterly winds. Consequently, we conclude that wind-forcing and shelf circulation are critical factors that influence the plume trajectories and the associated biogeochemical properties in coastal waters.

BGD
10, 19867–19893, 2013

1 Introduction

Despite its small geographic extent, the coastal ocean plays an important role in the global carbon cycle through the combined processes of net biological production and export of organic (Bauer and Bianchi, 2011) carbon as well as net carbon dioxide (CO_2) exchange with the atmosphere (Cai, 2011; Chen and Borges, 2009; Cai et al., 2006). Coastal oceans also face serious anthropogenic stresses that can alter shelf metabolism, for example, nitrogen enrichment and eutrophication (surface algal blooms) and the associated bottom water hypoxia (dissolved oxygen [DO] $< 2\,mg\,L^{-1}$), especially on large-river-dominated continental shelves (Rabalais et al., 2010; Rabouille et al., 2008). Physically, coastal oceans are characterized by a complex shelf circulation that is driven by variations in freshwater discharge, upwelling along the shelf edge, and local wind forcing (Lentz and Fewings, 2012). Variations in shelf circulation can have a major impact on the distribution of freshwater and associated nutrients (Bianchi et al., 2010). As coastal oceans are highly dynamic, how surface partial pressure of CO_2 ($p CO_2$) and bottom water hypoxia are influenced by circulation is poorly understood.

During summer, the Mississippi and Atchafalaya River plume is usually distributed along the Louisiana and Texas shelves (Cochrane and Kelly, 1986; Chu et al., 2005; Ohlmann and Niiler, 2005; Smith and Jacobs, 2005). This general summer pattern of Louisiana shelf circulation is greatly dependent on local wind forcing (Cochrane and Kelly, 1986; Ohlmann and Niiler, 2005; Smith and Jacobs, 2005). Simulation modeling confirms that the general circulation pattern was common in summer during the past decade (Zhang et al., 2012), including August 2007, when we conducted our study.

Shelf-wide summer hypoxia occurred repeatedly in bottom waters of the Louisiana shelf in the past decades (Turner et al., 2012). The magnitude and spatial extent of plume algal production and bottom water hypoxia are coupled and primarily controlled by nitrogen mass export from the Mississippi-Atchafalaya River (Green et al., 2008; Scavia et al., 2003; Turner et al., 2006), and secondarily by freshwater discharge and

BGD
10, 19867–19893, 2013

the strength of easterly winds on the Louisiana shelf (Forrest et al., 2011). The associated inorganic nitrogen flux in May (a time best correlated with plume phytoplankton production during summer) was comparable between the two years compared in our study, 1.48×10^{11} g N in 2007 and 1.55×10^{11} g N in 2009 (US Geological Survey data). Plume and hypoxic strength and areal extent were markedly different between the two years however (Turner et al., 2012; Bianchi et al., 2010; Forrest et al., 2011; Evans and Scavia, 2011). Hydrodynamic modeling suggests that coastal circulation in July 2009 differed from the normal pattern primarily because of persistent southerly winds along the Texas coast (Zhang et al., 2012). More continuous upwelling-favorable winds along the Louisiana coast were also observed than past two decades (Feng et al., 2013). In summer 2009, the weather was observed abnormal, e.g. temperature was cool in central North America and was the hottest July in Austin, Texas since 1854 (Ha et al., 2012; LeComte, 2010). The much smaller hypoxia event in July 2009 thus provides a good opportunity to understand how factors other than river freshwater and nutrient fluxes affect the biogeochemical and metabolic processes on the Louisiana shelf.

In this study, we compare two summers with contrasting shelf circulation: August 2007, which we consider typical and July 2009, which we consider unusual. We describe how sea surface salinity, surface water $p\mathrm{CO_2}$ and satellite-derived chlorophyll *a* (Chl *a*) differ between the two years. We discuss how this unusual physical condition affects air–sea CO_2 flux, the spatial extent of bottom water hypoxia, and the relationship between dissolved inorganic carbon (DIC) and DO in the bottom water of the Louisiana shelf.

2 Methods

Cruises were conducted in 18–24 August 2007 on board OSV *Bold*, and in 19–29 July 2009 on board R/V *Cape Hatteras* on the Louisiana shelf. Total of 125 bottom water DIC samples were collected from Niskin bottles using 250 mL borosilicate glass bottles which was thoroughly flushed with sample with extensive overflow (> 125 mL).

BGD
10, 19867–19893, 2013

DIC samples were preserved with 100 µL $HgCl_2$ and were measured shortly after the cruise by acidifying 0.5 mL of sample and quantifying the released CO_2 using an infrared gas analyzer (LI-COR® 6252). This DIC measurement had a precision of 0.1 % (Cai et al., 2010; Huang et al., 2012). DO concentrations were from the vertical conductivity, temperature, and depth (CTD) package and was calibrated by Winkler titration methods based on samples collected from the Niskin bottle.

For sea surface salinity and $p\mathrm{CO_2}$ measurements, seawater was sampled from the ship flow-through inlet at about one meter depth. $p\mathrm{CO_2}$ was measured by a flow-through system with a "shower head equilibrator plus a CO_2 analyzer (LI-COR 7000)" (Jiang et al., 2008). The LI-COR® 7000 was calibrated every 3.5 to 6 h using four certified gas standards, which had dry CO_2 values of 197.45, 400.57, and 594.65, and 975.26 ppm referenced against standards traceable to those of the National Institute of Standards and Technology. Area average of $p\mathrm{CO_2}$ values were gridded to a resolution of $0.1^\circ \times 0.1^\circ$ and were used to calculate the air–sea CO_2 flux by this equation:

$$\mathrm{CO_2\ flux} = k \times K_0 \times (p\mathrm{CO_2sw} - \mathrm{CO_2air}) \quad (1)$$

k represents the gas transfer velocity; K_0 is the solubility of CO_2 (Weiss, 1974); $p\mathrm{CO_2}$sw and $p\mathrm{CO_2}$air are the $p\mathrm{CO_2}$ in surface seawater and overlying atmosphere, respectively. Their difference expresses the CO_2 gradient across the air–sea interface. We applied the QuikSCAT (Quick Scatterometer) ocean surface winds data with a resolution of 0.25° and air–sea gas transfer coefficient estimated by Ho et al. (2006) to calculate air–sea CO_2 fluxes with methods given by Jiang et al. (2008).

SeaWiFS Chl *a* data were obtained from Ocean Watch Live Access Server of the National Oceanic and Atmospheric Administration (NOAA) and were used without colored dissolved organic matter correction to solely present the meso-scale trajectory of the river plume (Del Castillo et al., 2001). The slope of the DO-to-DIC relationship was determined by Type II regression considering uncertainties of DO and DIC.

3 Results

3.1 Distributions of sea surface salinity, SeaWiFS Chl *a*, and *T*–*S* relationship

Distribution of sea surface salinity in August 2007 was typical for the summer season on the Louisiana shelf (Fig. 1a). Salinity was lowest immediately adjacent to southwest pass of the Mississippi River. Salinities less than 30 were found to the east and west of the river's birdfoot delta and extended along the inner shelf towards Texas. The outer shelf between the delta and Texas had salinities greater than 30. Overall, lower salinity waters on the inner shelf and higher salinity waters on the outer shelf demonstrated that the freshwater plume was distributed throughout the inner Louisiana shelf in August 2007 (Fig. 1a). During July 2009, however, lower salinity waters (salinity less than 33) were confined mostly to the eastern shelf (east of 91.5° W) except for a small pocket immediately next to the Atchafalaya River and Bay. Lower salinity also extended across the outer shelf and ocean to the east of 91.5° W. On the western shelf, higher salinity water (> 33) was found on the inner to outer shelves (Fig. 1b).

The distribution of Chl *a* showed patterns of plume distribution similar to those based on salinity (Fig. 1c and d). High Chl *a* concentrations were observed along the coast in summer 2007 (Fig. 1c), demonstrating that the plume trajectory was narrow and extended eastward along the Louisiana and Texas shelf. In contrast, Chl *a* distribution was high and extended offshore on the eastern Louisiana shelf in July 2009 (Fig. 1d).

The impact of different circulation patterns between August 2007 and July 2009 was also evident in water column temperature to salinity (*T*–*S*) distributions. In the typical year, August 2007, we see low salinity and high temperature in shallow waters along the shelf; and high salinity and high temperature in deeper waters just off the shelf (Fig. 2). In contrast, in July 2009, temperature and salinity were both lower on the eastern shelf (indicating more freshwater) while temperature and salinity were both slightly higher on the western shelf. This difference in *T*–*S* patterns between eastern and western shelves was consistent with sea surface salinity distributions. Additionally, despite distributions of freshwater and river plume differed between years, the monthly average

BGD
10, 19867–19893, 2013

river discharge of July and August remained similar between in 2007 (15 800 $m^3 s^{-1}$) and 2009 (17 500 $m^3 s^{-1}$, USGS data).

3.2 pCO_2 distributions and air–sea CO_2 fluxes

Surface pCO_2 distributions also differed greatly between August 2007 and July 2009. Typically surface pCO_2 values show strong cross-shelf gradients (i.e. low in the inner shelf and high in the outer shelf) and a weak alongshore gradient, and August 2007 was no different (Fig. 3a). In stark contrast, in July 2009, pCO_2 was high in the western inner shelf, resulting in a strong east-to-west alongshore gradient (i.e. low pCO_2 in the east and high in the west) (Fig. 3b). These spatial patterns in surface pCO_2 and Chl *a* in July 2009 were consistent with the distribution of T–S and sea surface salinity, showing that these biogeochemical contrasts were affected by the altered plume location and shelf circulation.

To systematically compare air–sea CO_2 fluxes on the Louisiana shelf between the two cruises, the smaller survey area of August 2007 (generally within the 50 m isobath) was adopted for reference. We found that the shelf acted as a weak CO_2 sink to the atmosphere (-1.70 ± 0.20 mmol $m^{-2} d^{-1}$) in August 2007, but a source (2.24 ± 0.13 mmol $m^{-2} d^{-1}$) in July 2009. The difference between years was greater in the western area (ΔCO_2 flux = 4.96 mmol $m^{-2} d^{-1}$) than in the eastern area (ΔCO_2 flux = 2.7 mmol $m^{-2} d^{-1}$). This large difference in behavior was mainly due to the difference in pCO_2 levels in the western area between years (Table 1).

3.3 Bottom water DO and DIC

Bottom water DO and DIC distributions also varied between years (Fig. 4). Typically, hypoxic bottom waters stretch alongshore following the 20–45 m isobaths on the Louisiana shelf. In August 2007 the areal hypoxic water coverage was ~ 20 000 km^2 (Fig. 4a). Relatively high DIC concentrations co-occurred with low O_2 or hypoxic waters. In contrast, bottom water hypoxia was only observed on the eastern shelf in July 2009,

BGD
10, 19867–19893, 2013

displaying a much smaller hypoxic area of only 2000–4000 km^2 near the Mississippi River mouth (Fig. 4b). Highest DIC concentrations were consistent with the distribution of hypoxia (Fig. 4c and d).

In summary, the distributions of bottom hypoxia waters were consistent with the surface distributions of sea surface salinity, Chl *a* and pCO_2, i.e. alongshore in August 2007 and confined to the eastern shelf in July 2009.

4 Discussion

4.1 Wind forcing and surface shelf circulation in summer

Wind forcing and shelf circulations differed greatly between summer 2007 and 2009; and showed such contrast began in Jun. Based on the record of southerly wind from a buoy (NOAA station #42043) near Galveston, Texas, we observed: (1) more southerly winds in summer 2009 than in summer 2007 (Fig. 6a); and (2) these southerly winds in 2009 were stronger than in 2007 (Fig. 6b). Upwelling-favorable winds along the Louisiana coast also persisted from June to July in 2009 (Feng et al., 2013). A continuous modeled shelf circulation, including these two summers, also demonstrated the variations began from June until July (Xue et al., 2013, http://omgsrv1.meas.ncsu.edu:8080/ocean-circulation/carbon.jsp). For spatial variations, we used QuikSCAT wind fields (Fig. 5a and b) to demonstrate wind forcing, and applied the Hybrid Coordinate Ocean Model (HYCOM, the Naval Research Laboratory, http://hycom.org/, HYCOM + NCODA Gulf of Mexico 1/25° Analysis) modeled sea surface currents (Fig. 5c and d) to illustrate shelf circulation patterns in August 2007 and July 2009. The monthly average wind field was easterly and weak over the entire Gulf of Mexico in August 2007, which was typical (Fig. 5a). The modeled shelf circulation in August 2007 (Fig. 5c) was also typical of the summer. However, this wind forcing was clockwise over the Gulf of Mexico in July 2009, showing mostly southerly winds along the Texas and Louisiana coasts (Fig. 5b). The combination of modeled shelf circulation (Fig. 5d) and the distribution of T–S (Fig. 2) suggested that high salinity waters on the western inner shelf was likely due to a particularly strong inner coastal current from the southern Texas coast encroaching over the inner western Louisiana shelf (Box A in Fig. 5d).

Such different temporal and meso-scale wind forcing in summer 2009 (Figs. 5b and 6) is likely due to the unusual global weather in June and July 2009, i.e. the weather was characterized by abnormally cool in three mid-latitude regions, including central North America (Ha et al., 2012); and it was the hottest July in Austin, Texas, since 1854 (LeComte, 2010). The meso-scale wind forcing was favorable for the northward coastal current running up along Texas and over to Louisiana and also for cross-shelf components near the Mississippi River delta in summer 2009 (Fig. 5d) (Lentz and Fewings, 2012). Modeled shelf circulations considered meso-scale wind forcing (HYCOM, Zhang et al., 2012; Xue et. al., 2013) are consistent with and support our meso-scale measured distributions of sea surface salinity and $p\mathrm{CO_2}$ (Fig. 1b and d). Furthermore, relationship between this shelf circulation characterized by cross-shelf components and southerly wind forcing was also suggested by numerical models presented by Zhang et al. (2012) and Chu et al. (2005).

4.2 The biogeochemical impact on plume and surrounding surface waters

Shelf circulation and the location and strength of river inputs obviously plays a major role in the resultant distributions of surface $p\mathrm{CO_2}$ and the air–sea CO_2 fluxes in this region as well as the distribution of primary production (Chen et al., 2000). Net primary production in the plume draws down CO_2, leaving undersaturated $p\mathrm{CO_2}$ values with respect to the atmosphere. These undersaturated $p\mathrm{CO_2}$ waters are typically distributed alongshore, as we observed in August 2007 and in previous summer studies (Lohrenz et al., 2010; Lohrenz and Cai, 2006). However, the relocated plume trajectory under the altered shelf circulation in July 2009 changed the location of associated biogeochemical characteristics, enhanced primary production and organic carbon export, to focusing on eastern Louisiana shelf. In shifting the region of CO_2 drawdown, the western shelf area became a strong CO_2 source in 2009 during summer; similarly, the eastern shelf shifted from being a strong sink in 2007 to a weak source in 2009 (Table 1).

4.3 The impact of shifting biological production on bottom-water hypoxia

As the riverine nitrogen fluxes that typically correlate well with phytoplankton biomass accumulation were similar in May 2007 and May 2009, the extent and distribution of summer hypoxia would also be expected to be similar ($\sim 23\,500\,km^2$ predicted for July 2009, Turner et al., 2012). Rabalais et al. noted that it was very different however (Rabalais et al. webpage "Hypoxia in the Northern Gulf of Mexico"; http://www.gulfhypoxia.net/, i.e. $20\,500\,km^2$ during 12–19 July 2007 and $8000\,km^2$ during 12–19 July 2009).

Hypoxia in the Louisiana shelf is caused primarily by both "hypoxia potential" (planktonic biomass accumulated in the region around the plume) and the stratification (Hetland and DiMarco, 2008). The distribution of stratification index (change of Sigma-T between the bottom and surface layers) suggests that stratification did not differ greatly between these two years at the meso-scale (Fig. 7). The hypoxic potential (as measured by low pCO$_2$, high Chl *a*) was high in the entire inner shelf in summer 2007 but was only high on the eastern shelf and low (high pCO$_2$, low Chl *a*) on the western shelf in summer 2009 (Figs. 1c and d and 3). Hence, the difference in hypoxia between years was due solely to differences in where phytoplankton biomass accumulation occurred, which in turn was related to the altered circulation brought about by an unusual summer wind pattern.

This conclusion is consistent with earlier finding that hypoxia area was affected by large scale circulation (Wiseman et al., 1997), and is also consistent with the importance of easterly wind or westerly wind in the estimation of hypoxia coverage in addition to river discharge and nitrogen concentration (Forrest et al., 2011; Feng et al., 2012).

BGD
10, 19867–19893, 2013

4.4 Bottom water DO-to-DIC relationships

The river-to-sea mixing process alone cannot explain the DO and DIC variations in the bottom water during summer. In August 2007, DO and DIC typically mirror each other along the salinity gradient, especially in hypoxic waters, as was seen in August 2007, albeit with some variability. (Fig. 8a and b). To better illustrate the DO-to-DIC relationships (Fig. 8c), we analyze bottom waters along the 10 and 20 m isobaths, which parallel the trajectory of plume waters and encompasses much of hypoxic zone (Fig. 4a and c). Bottom waters inshore of this zone varied greatly in salinity and their compositions were biogeochemically more influenced by the river end-member (low salinity, shallow depth, and high DO). We define these inner waters as "brackish waters" (water depth < 20 m, DO < 150 µM, DIC < 2200 µM). Bottom waters offshore the 20 m isobath showed little salinity variation (< 0.4) and were similar in composition to the open ocean end-member (high salinity, deeper depth and high DO). We define these waters as "high salinity waters" (depth > 20 m and DO < 150 µM).

The slopes of DO-to-DIC relationships show the importance of respiration. For brackish water, the slope was 1.0 ± 0.2 ($R^2 = 0.826$); and for high salinity waters, the slope was 1.2 ± 0.1 ($R^2 = 0.836$). Both slopes are similar to Redfield stoichiometry, i.e. the O/C molar ratio is 1.30 (138/106, Redfield, 1958). Strauss et al. (2012) also reported that the signal of δ^{13}C-DIC and DO relationships were close to respiration of organic matter with Redfield stoichiometry on the inner Louisiana shelf. Such Redfield-type respiration has been observed in other coastal waters as well (Cantoni et al., 2012; Maske et al., 2010).

Respiration also contributed to bottom water DO and DIC concentrations in July 2009, but unlike in 2007, we found higher DIC than expected from O_2 consumption (Fig. 9). As the hypoxia was diminishing when we observed, we suggest that the observed high DIC was a legacy of previous hypoxia. Hypoxia disappeared while high DIC persisted at the time of our observation because of the 20 % faster gas transfer velocity of O_2 than CO_2 and the strong carbonate buffering capacity and its control on

CO_2 concentration (Sarmiento and Gruber, 2006; Cai et al., 1999; DeGrandpre et al., 1998; Zhai et al., 2009).

5 Summary

Shelf circulation plays a major role in the distribution of salinity, biological communities, community metabolism, and the biogeochemical properties, such as Chl *a*, DO, pCO_2, and DIC values on the Louisiana shelf. Deviations from normal weather can have a profound influence on the typical distribution of these properties and processes. Under typical summer conditions as in August 2007, the Mississippi and Atchafalaya River plume is confined to the shelf in a westward alongshore direction. Under different climate conditions however, the Mississippi and Atchafalaya River plume shifts accordingly. In summer 2009, the plume was confined to the eastern Louisiana shelf, with significant cross-shelf exchange. The shift in shelf circulation was highly related to local wind forcing in our study, i.e., from the typical easterly winds to atypical southerly winds in summer. Changes in shelf circulation resulted in shifting the Louisiana shelf from a neutral status to a weak source of atmospheric CO_2. The change in circulation also caused a shift in where the plume algal bloom settled. In 2009, hypoxia shifted to just off the Mississippi River delta with a decrease in areal extent. Therefore, hypoxia is limited to zones that plume derived organic matter overlaps with water stratification.

We conclude that while the distribution and areal extent of shelf surface water production and bottom water hypoxia are well predicted by river nitrogen flux under typical summer conditions, shifts in meso-scale weather can alter both the magnitude and location of the productive and low pCO_2 surface area and the bottom hypoxic waters. Shifts in circulation can alter the spatial distribution of air–sea CO_2 fluxes. Regional climate change will likely have a large impact on coastal biogeochemical processes in this region of the northern Gulf of Mexico brought about by altered wind regimes and consequent shifts in shelf circulation.

BGD
10, 19867–19893, 2013

Acknowledgements. We thank the captains and crews of OSV *Bold* and R/V *Cape Hatteras* for their support, and M. C. Murrell and S. E. Lohrenz for assistance and discussion. We also thank the National Science Foundation (OCE-0752110 to Cai), the National Aeronautics and Space Administration (NNX10AU06G Cai), and the BP-funded Gulf of Mexico Research Initiative RFP-II award (GoMRI-020 to Cai and Hu) for providing funding.

References

Bianchi, T. S., DiMarco, S. F., Cowan Jr., J. H., Hetland, R. D., Chapman, P., Day, J. W., and Allison, M. A.: The science of hypoxia in the Northern Gulf of Mexico: a review, Sci. Total Environ., 408, 1471–1484, 2010.

Bauer, J. E. and Bianchi, T. S.: Dissolved organic carbon cycling and transformation, in: Treatise on Estuarine and Coastal Science, edited by: Wolanski, E. and McLusky, D., Academic Press, Waltham, 7–67, 2011.

Cai, W.-J.: Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?, Annu. Rev. Mar. Sci., 3, 123–145, doi:10.1146/annurev-marine-120709-142723, 2011.

Cai, W.-J., Pomeroy, L. R., Moran, M. A., and Wang, Y.: Oxygen and carbon dioxide mass balance for the estuarine-intertidal marsh complex of five rivers in the southeastern US, Limnol. Oceanogr., 44, 639–649, 1999.

Cai, W.-J., Dai, M., and Wang, Y. C.: Air–sea exchange of carbon dioxide in ocean margins: a province-based synthesis, Geophys. Res. Lett., 33, L12603, doi:10.1029/2006GL026219, 2006.

Cai, W.-J., Hu, X., Huang, W.-J., Jiang, L.-Q., Wang, Y., Peng, T.-H., and Zhang, X.: Alkalinity distribution in the western North Atlantic Ocean margins, J. Geophys. Res., 115, C08014, doi:10.1029/2009jc005482, 2010.

Cantoni, C., Luchetta, A., Celio, M., Cozzi, S., Raicich, F., and Catalano, G.: Carbonate system variability in the Gulf of Trieste (North Adriatic Sea), Estuar. Coast. Shelf S., 115, 51–61, doi:10.1016/j.ecss.2012.07.006, 2012.

Chen, C.-T. A. and Borges, A. V.: Reconciling opposing views on carbon cycling in the coastal ocean: continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2, Deep-Sea Res. Pt. II, 56, 578–590, 2009.

Chen, X., Lohrenz, S. E., and Wiesenburg, D. A.: Distribution and controlling mechanisms of primary production on the Louisiana-Texas continental shelf, J. Marine Syst., 25, 179–207, 2000.
Chu, P. P., Ivanov, L. M., and Melnichenko, O. V.: Fall–winter current reversals on the Texas–Louisiana continental shelf, J. Phys. Oceanogr., 35, 902–910, doi:10.1175/jpo2703.1, 2005.
Cochrane, J. D. and Kelly, F. J.: Low-frequency circulation on the Texas–Louisiana continental shelf, J. Geophys. Res.-Oc. Atm., 91, 10645–10659, doi:10.1029/JC091iC09p10645, 1986.
DeGrandpre, M. D., Hammar, T. R., and Wirick, C. D.: Short-term $p\mathrm{CO_2}$ and O_2 dynamics in California coastal waters, Deep-Sea Res. Pt. II, 45, 1557–1575, doi:10.1016/s0967-0645(98)80006-4, 1998.
Evans, M. A. and Scavia, D.: Forecasting hypoxia in the Chesapeake Bay and Gulf of Mexico: model accuracy, precision, and sensitivity to ecosystem change, Environ. Res. Lett., 6, 015001, doi:10.1088/1748-9326/6/1/015001, 2011.
Feng, Y., DiMarco, S. F., and Jackson, G. A.: Relative role of wind forcing and riverine nutrient input on the extent of hypoxia in the northern Gulf of Mexico, Geophys. Res. Lett., 39, L09601, doi:10.1029/2012gl051192, 2012.
Feng, Y., Fennel, K., Jackson, G. A., DiMarco, S. F., and Hetland, R. D.: A model study of the response of hypoxia to upwelling-favorable wind on the northern Gulf of Mexico shelf, J. Mar. Syst., doi:10.1016/j.jmarsys.2013.11.009, in press, 2013.
Forrest, D. R., Hetland, R. D., and DiMarco, S. F.: Multivariable statistical regression models of the areal extent of hypoxia over the Texas–Louisiana continental shelf, Environ. Res. Lett., 6, 045002, doi:10.1088/1748-9326/6/4/045002, 2011.
Green, R. E., Breed, G. A., Dagg, M. J., and Lohrenz, S. E.: Modeling the response of primary production and sedimetation to variable nitrate loading in the Mississippi River plume, Cont. Shelf Res., 28, 1451–1465, 2008.
Ha, K.-J., Chu, J.-E., Lee, J.-Y., Wang, B., Hameed, S. N., and Watanabe, M.: What caused the cool summer over northern Central Asia, East Asia and central North America during 2009?, Environ. Res. Lett., 7, 044015, doi:10.1088/1748-9326/7/4/044015, 2012.
Hetland, R. D. and DiMarco, S. F.: How does the character of oxygen demand control the structure of hypoxia on the Texas–Louisiana continental shelf?, J. Mar. Syst., 70, 49–62, 2008.

Ho, D. T., Law, C. S., Smith, M. J., Schlosser, P., Harvey, M., and Hill, P.: Measurements of air–sea gas exchange at high wind speeds in the Southern Ocean: implications for global parameterizations, Geophys. Res. Lett., 33, L16611, doi:10.1029/2006gl026817, 2006.

Huang, W.-J., Wang, Y., and Cai, W.-J.: Assessment of sample storage techniques for total alkalinity and dissolved inorganic carbon in seawater, Limnol. Oceanogr.-Meth., 10, 711–717, doi:10.4319/lom.2012.10.711, 2012.

Jiang, L.-Q., Cai, W.-J., Wang, Y., Wanninkhof, R., and Lüger, H.: Air–sea CO_2 fluxes on the US South Atlantic Bight: spatial and seasonal variability, J. Geophys. Res., 113, C07019, doi:10.1029/2007jc004366, 2008.

LeComte, D.: US weather highlights for 2009: the year without a summer, Weatherwise, 63, 15–23, doi:10.1080/00431671003732606, 2010.

Lentz, S. J. and Fewings, M. R.: The wind- and wave-driven inner-shelf circulation, Annu. Rev. Mar. Sci., 4, 317–343, doi:10.1146/annurev-marine-120709-142745, 2012.

Lohrenz, S. E. and Cai, W.-J.: Satellite ocean color assessment of air–sea fluxes of CO_2 in a river-dominated coastal margin, Geophys. Res. Lett., 33, L01601, doi:10.1029/2005GL023942, 2006.

Lohrenz, S. E., Cai, W.-J., Chen, F., Chen, X., and Tuel, M.: Seasonal variability in air–sea fluxes of CO_2 in a river-influenced coastal margin, J. Geophys. Res., 115, C10034, doi:10.1029/2009jc005608, 2010.

Maske, H., Medrano, R. C., Castro, A. T., Mercado, A. J., Jauregui, C. O. A., Castro, G. G., and Ochoa, J.: Inorganic carbon and biological oceanography above a shallow oxygen minimum in the entrance to the Gulf of California in the Mexican Pacific, Limnol. Oceanogr., 55, 481–491, doi:10.4319/lo.2010.55.2.0481, 2010.

Morey, S. L., Schroeder, W. W., O'Brien, J. J., and Zavala-Hidalgo, J.: The annual cycle of riverine influence in the eastern Gulf of Mexico basin, Geophys. Res. Lett., 30, 1867, doi:10.1029/2003GL017348, 2003.

Ohlmann, J. C. and Niiler, P. P.: Circulation over the continental shelf in the northern Gulf of Mexico, Prog. Oceanogr., 64, 45–81, 2005.

Rabalais, N. N., Turner, R. E., Justiæ, D., Dortch, Q., Wiseman, W., and Sen Gupta, B.: Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf, Estuar. Coast., 19, 386–407, 1996.

BGD
10, 19867–19893, 2013

Impacts of a weather event on shelf circulation and CO_2 and O_2 dynamics

W.-J. Huang et al.

Rabalais, N. N., Díaz, R. J., Levin, L. A., Turner, R. E., Gilbert, D., and Zhang, J.: Dynamics and distribution of natural and human-caused hypoxia, Biogeosciences, 7, 585–619, doi:10.5194/bg-7-585-2010, 2010.

Rabouille, C., Conley, D. J., Dai, M. H., Cai, W. J., Chen, C. T. A., Lansard, B., Green, R., Yin, K., Harrison, P. J., Dagg, M., and McKee, B.: Comparison of hypoxia among four river-dominated ocean margins: the Changjiang (Yangtze), Mississippi, Pearl, and Rhône rivers, Cont. Shelf Res., 28, 1527–1537, 2008.

Redfield, A. C.: The biological control of chemical factors in the environment, Am. Sci., 46, 205–221, 1958.

Sarmiento, J. L. and Gruber, N.: Ocean Biogeochemical Dynamics, vol. 503, Princeton University Press, Princeton, New Jersey, USA, 2006.

Scavia, D., Rabalais, N. N., Turner, R. E., Justiæ, D., and William, J. Wiseman, J.: Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load, Limnol. Oceanogr., 48, 951–956, 2003.

Smith, S. R. and Jacobs, G. A.: Seasonal circulation fields in the northern Gulf of Mexico calculated by assimilating current meter, shipboard ADCP, and drifter data simultaneously with the shallow water equations, Cont. Shelf Res., 25, 157–183, 2005.

Strauss, J., Grossman, E. L., and DiMarco, S. F.: Stable isotope characterization of hypoxia-susceptible waters on the Louisiana shelf: tracing freshwater discharge and benthic respiration, Cont. Shelf Res., 47, 7–15, doi:10.1016/j.csr.2012.07.020, 2012.

Turner, R. E., Rabalais, N. N., and Justic, D.: Predicting summer hypoxia in the northern Gulf of Mexico: riverine N, P, and Si loading, Mar. Pollut. Bull., 52, 139–148, doi:10.1016/j.marpolbul.2005.08.012, 2006.

Turner, R. E., Rabalais, N. N., and Justiæ, D.: Predicting summer hypoxia in the northern Gulf of Mexico: redux, Mar. Pollut. Bull., 64, 319–324, doi:10.1016/j.marpolbul.2011.11.008, 2012.

Weiss, R. F.: Carbon dioxide in water and seawater: the solution of a non-ideal gas, Mar. Chem., 2, 203–215, 1974.

Wiseman, W. J., Rabalais, N. N., Turner, R. E., Dinnel, S. P., and MacNaughton, A.: Seasonal and interannual variability within the Louisiana coastal current: stratification and hypoxia, J. Marine Syst., 12, 237–248, 1997.

Xue, Z., He, R., Fennel, K., Cai, W.-J., Lohrenz, S., and Hopkinson, C.: Modeling ocean circulation and biogeochemical variability in the Gulf of Mexico, Biogeosciences, 10, 7219–7234, doi:10.5194/bg-10-7219-2013, 2013.

Zhai, W. D., Dai, M., and Cai, W.-J.: Coupling of surface pCO_2 and dissolved oxygen in the northern South China Sea: impacts of contrasting coastal processes, Biogeosciences, 6, 2589–2598, doi:10.5194/bg-6-2589-2009, 2009.
Zhang, X., Hetland, R. D., Marta-Almeida, M., and DiMarco, S. F.: A numerical investigation of the Mississippi and Atchafalaya freshwater transport, filling and flushing times on the Texas–Louisiana Shelf, J. Geophys. Res., 117, C11009, doi:10.1029/2012jc008108, 2012.

BGD
10, 19867–19893, 2013

Impacts of a weather event on shelf circulation and CO_2 and O_2 dynamics

W.-J. Huang et al.

Table 1. Average pCO_2 (µatm) and air–sea CO_2 fluxes ($mmol\,m^{-2}\,d^{-1}$, positive values indicate a CO_2 flux direction to the atmosphere) in the reference area and western and eastern areas.

	Reference area pCO_2	Reference area CO_2 flux	Western area CO_2 flux	Eastern area CO_2 flux
Aug 2007	347.8	−1.70	−0.73	−2.87
Jul 2009	403.7	2.24	4.23	−0.17
ΔCO_2 flux		3.94	4.96	2.7

The reference area is the same as the survey area in August 2007. The western and eastern Louisiana shelves were divided by longitude 91.5° W.

BGD
10, 19867–19893, 2013

BGD

10, 19867–19893, 2013

Impacts of a weather event on shelf circulation and CO_2 and O_2 dynamics

W.-J. Huang et al.

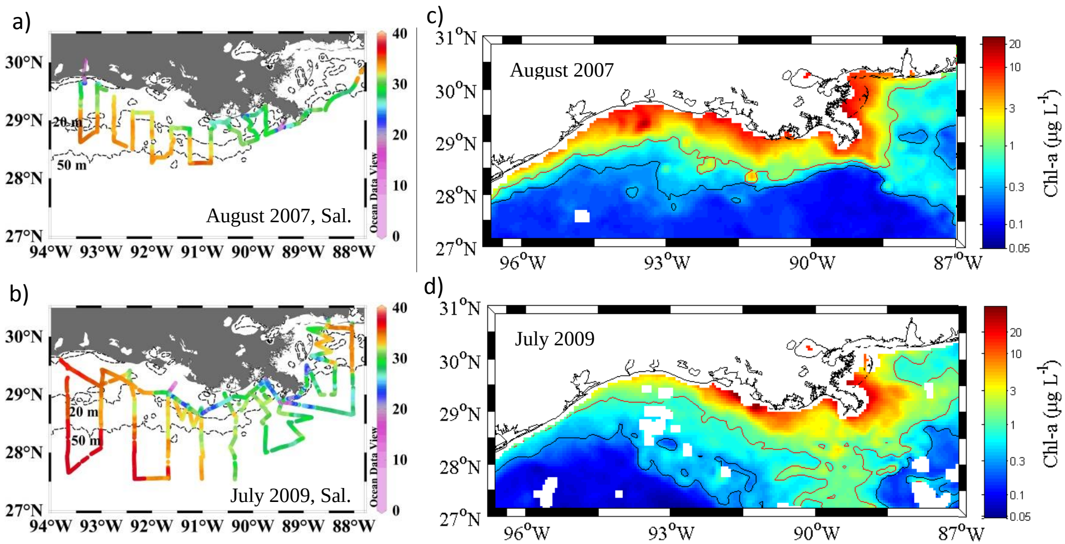

Fig. 1. Distribution of surface seawater salinity **(a, b)** and satellite monthly Chl *a* **(c, d)**. Lower salinity waters were distributed on the inner shelf, and higher salinity waters were distributed on the outer shelf in August 2007 **(a)**. Low salinity waters were distributed mostly to the eastern shelf (both inner and outer); high salinity waters were observed on the inner western shelf, except the Atchafalaya Bay and its adjacent areas in July 2009 **(b)**. Satellite monthly Chl *a* concentrations with contour lines of 0.3 (black) and 1 $\mu g\,L^{-1}$ (red) displayed an alongshore distribution of river plume for August 2007 (**c** from SeaWiFS) and a cross-shelf plume for July 2009 (**d** from MODIS). We used MODIS for July 2009, because the SeaWiFS Chl *a* image was covered by cloud in the study area.

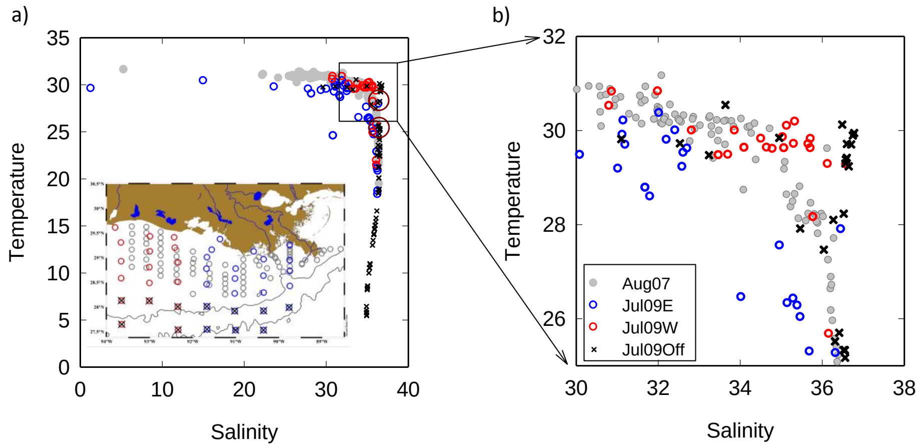

Fig. 2. Temperature to salinity diagram during August 2007 (gray solid dots) and July 2009 (circles and × markers), displaying the mixing process between fresh water and deep seawaters **(a)** with its corresponding station map (the inserted figure in **a**). An enlarged diagram **(b)** focusing on the continental shelf, showing the variation of T–S relationship between August 2007 and July 2009. The temperature and salinity of the western shelf waters (red circles) were higher than waters in August 2007 and was close to those waters from outer shelf, suggesting the waters on the western shelf were affected by outer shelf waters (× markers). The temperature and salinity from the eastern shelf (blue circles) were generally lower than waters in August 2007, showing a "shortcut" mixing process between freshwater and deep seawaters.

BGD
10, 19867–19893, 2013

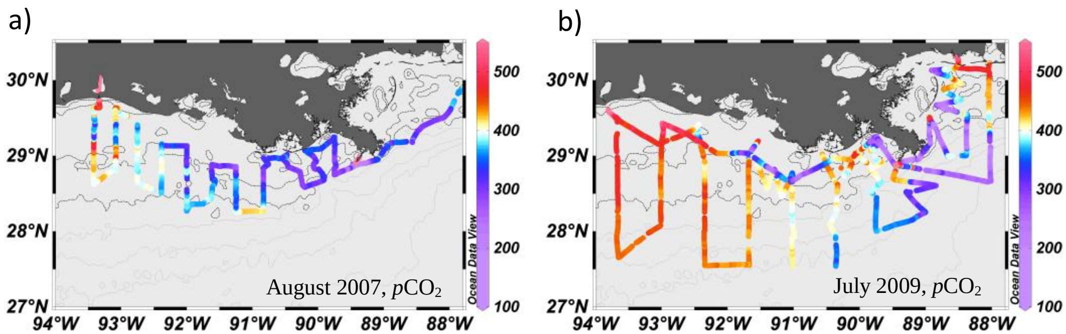

Fig. 3. Distributions of sea surface pCO_2. Lower pCO_2 waters were also found in the inner shelf and higher pCO_2 were located in the outer shelf in August 2007 **(b)**, except the waters in the Mississippi River channel and near the lakes or bays showed high pCO_2. In contrast, low pCO_2 waters were observed on the eastern shelf (from inner to outer shelf) and high pCO_2 were observed on the western shelf. The distributions of sea surface pCO_2 showed the river plume was narrow and along shore in August 2007 but was promoted to the eastern shelf in July 2009.

BGD
10, 19867–19893, 2013

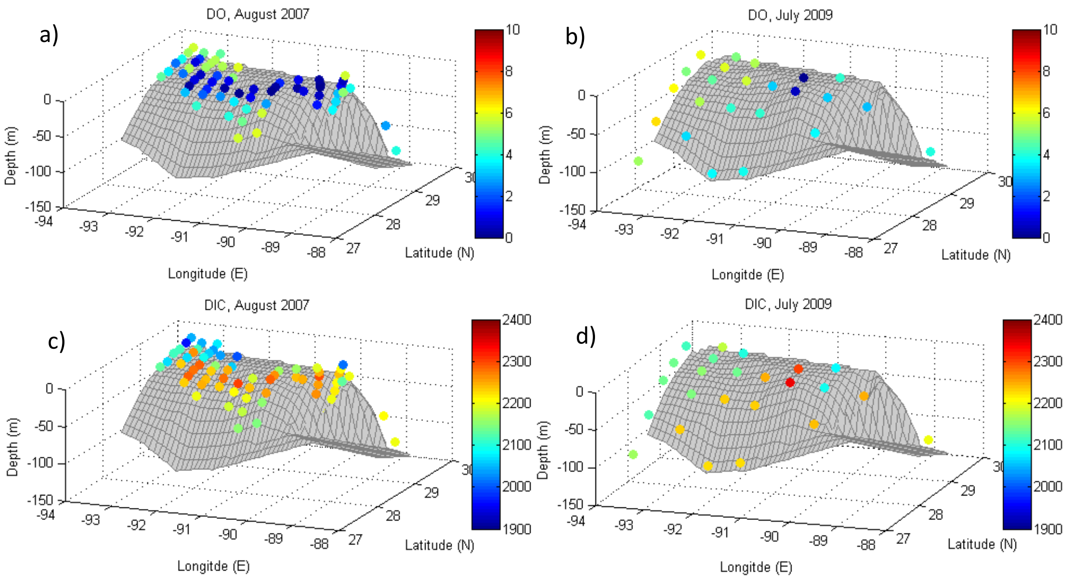

Fig. 4. Spatial distributions of bottom water DO ($mg\,L^{-1}$) and DIC (µM) concentrations on the Louisiana Shelf. Hypoxic water (DO < 2 $mg\,L^{-1}$) **(a)** and high DIC concentrations **(b)** were observed along the coast in August 2007. In contrast, this situation was only found in the vicinity of the Atchafalaya Bay in July 2009 **(c, d)**.

BGD
10, 19867–19893, 2013

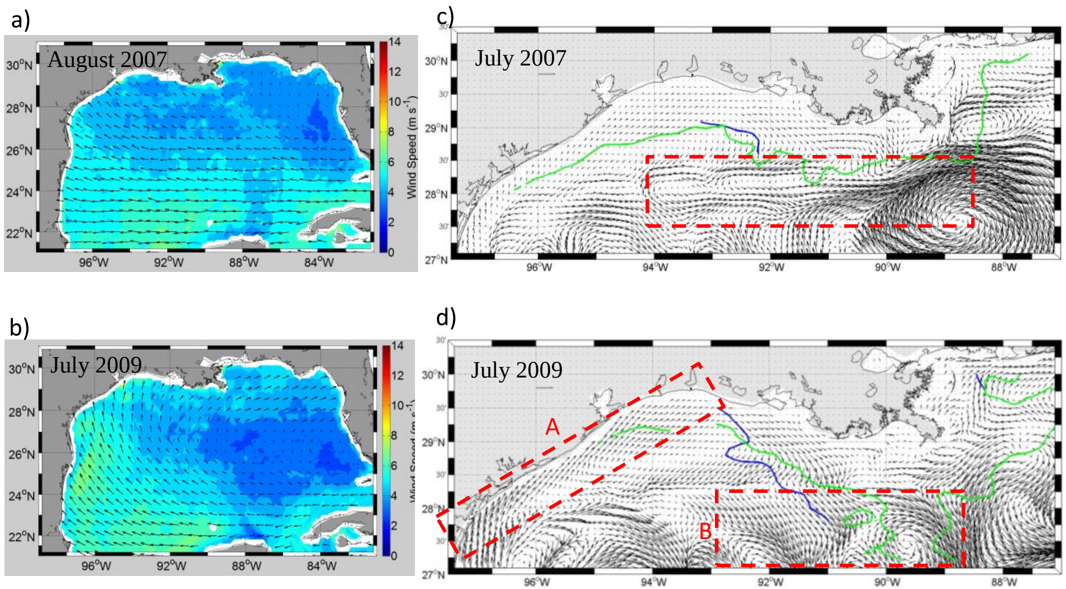

Fig. 5. Distributions of QuikSCAT wind forcing **(a, b)** and HYCOM simulated surface currents **(c, d)**. Easterly winds dominated the Gulf of Mexico in August 2007 **(a)** and a clockwise cyclonic wind forcing dominated in July 2009, resulting in southerly wind dominated the Louisiana–Texas shelf **(b)**. The shelf circulation was dominated by strong eastward currents and westward currents in the red box of **(c)** in August 2007, and was characterized by a strong northward current along Texas coast (the A red box in **d**) and dominated by more cross-shelf components in July 2009 (the B red box in **d**). In **(c)** and **(d)**, blue lines are the contour line of salinity 33 and red lines showed the contour lines of Chl *a* concentration of 1 mg L^{-1} in Fig. 1.

BGD
10, 19867–19893, 2013

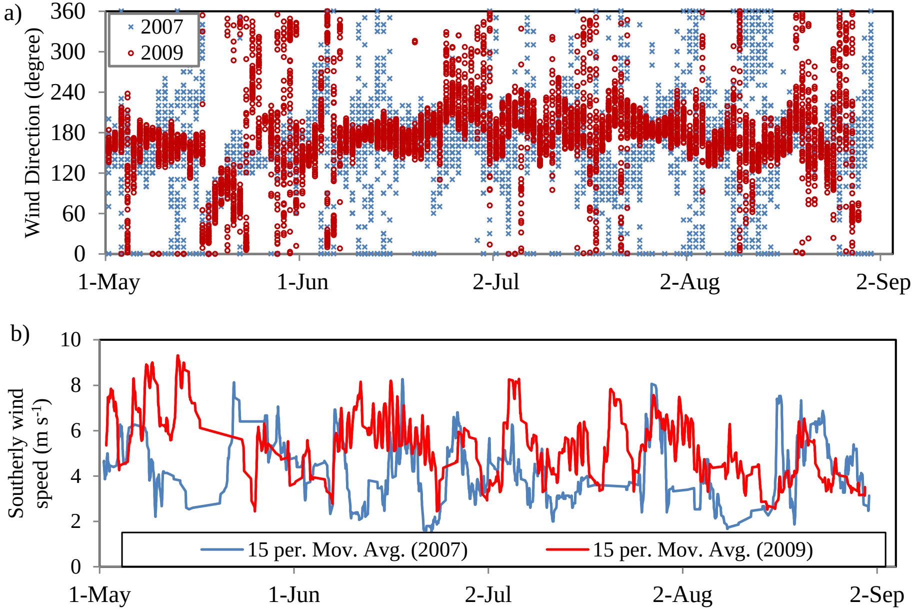

Fig. 6. Time series variation of wind direction **(a)** and southerly wind speed **(b)** near Galveston, Texas, from May to August. The data were obtained from the NOAA Buoy, station #42043, locating at 28.982° N, 94.919° W. Southerly winds were more continuous in summer 2009 than 2007 **(a)**, and were also stronger in 2009 **(b)**.

BGD
10, 19867–19893, 2013

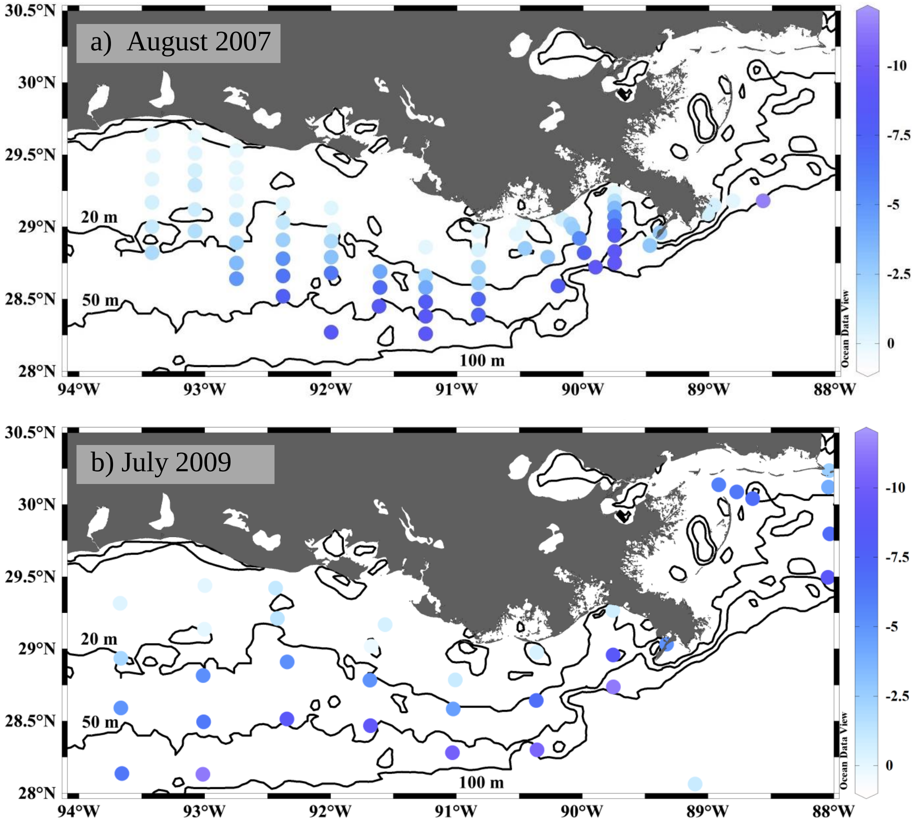

Fig. 7. Distributions of stratification index in August 2007 **(a)** and July 2009 **(b)**. The definition of stratification index is the difference of sigma-T between surface and bottom waters. Stratification was observed mostly along the coast between 20 to 50 m isobaths in these two months.

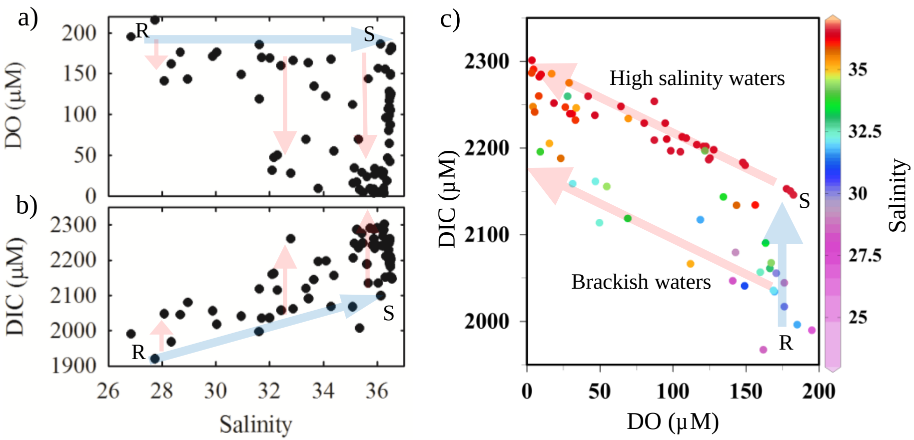

Fig. 8. The relationships of DO to salinity **(a)**, DIC to salinity **(b)**, and DO and DIC concentrations **(c)** in August 2007. Mixing process (blue arrows) and respiration (red arrows) dominated the variations of DO and DIC concentrations in August 2007. River endmember (R) showed lower salinity and lower DIC concentration, and seawater endmember (S) showed higher salinity and higher DIC concentration. The relationship between DO and DIC in the bottom water can be observed in brackish waters and seawaters individually **(c)**, which were separated by an alongshore isobaths zone between 10 and 20 m. The slopes of DO-to-DIC relationship (1.0 ± 0.2, R^2 = 0.826 for brackish water; and 1.2 ± 0.1, R^2 = 0.836 for high salinity waters) were both close to the estimation of Redfield respiration (represented by two red arrows in **c**).

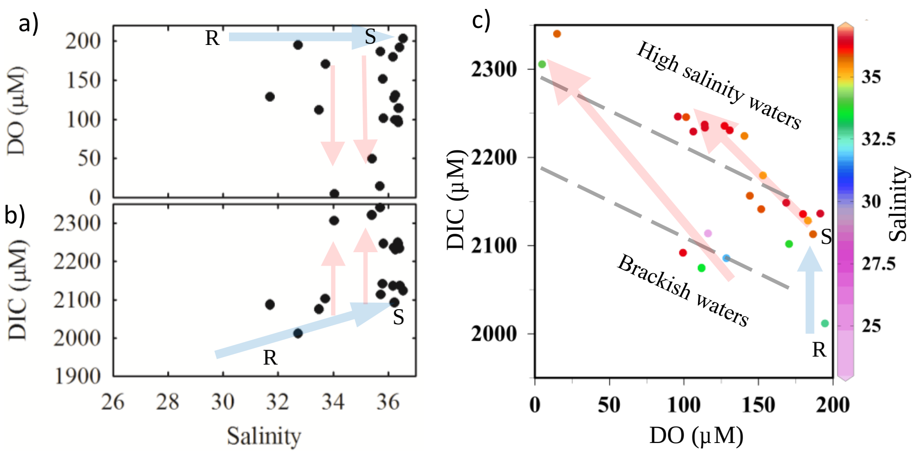

Fig. 9. The relationships of DO to salinity **(a)**, DIC to salinity **(b)**, and DO and DIC concentrations **(c)** in July 2009. Respiration (red arrows) dominated the variations of DO and DIC concentrations in addition to river (R) to sea (S) mixing process (blue arrows) in July 2009. But the slopes of DO-to-DIC relationship were higher than those in August 2007 and also higher than Redfield-ratio predicted lines (gray dash lines), might due to faster DO gas transfer velocity.

BGD
10, 19867–19893, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion