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Spatial and temporal variability of air-sea CO_2 exchange of alongshore waters in summer near Barrow, Alaska

Hiroki Ikawa [a,b,*], Walter C. Oechel [a]

[a] Global Change Research Group, San Diego State University, 5500 Campanile Dr., San Diego, CA 92182-4614, USA
[b] International Arctic Research Center, University of Alaska, 930 Koyukuk Dr., PO Box 757340, Fairbanks, AK 99775-7340, USA

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A B S T R A C T

Alongshore water off Barrow, Alaska is a useful area for studying the carbon cycle of the Arctic coastal sea, because the different coastal characteristics extant in the area likely represent much larger regions of the coastal water of the western Arctic Ocean. Especially noteworthy is the inflow shelf water transferred northward by the Arctic Coastal Current into the Chukchi Sea from the North Pacific and turbid water in the Elson Lagoon where a significant amount of coastal erosion has been reported along the extensive coastal line and where a part of the water from the lagoon drains into the Beaufort Sea adjacent to the Chukchi Sea. To investigate spatial and temporal variations of air-sea CO_2 flux (CO_2 flux) of the alongshore water, partial pressure of CO_2 of surface seawater (pCO_{2sw}) was measured in summer, 2007 and 2008, and CO_2 flux was directly measured by eddy covariance at a fixed point for the Beaufort Sea in summer 2008. Measured pCO_{2sw} in the Chukchi Sea side was the lowest in the beginning of the measurement season and increased later in the season both in 2007 and 2008. The average CO_2 flux estimated based on pCO_{2sw} in the Chukchi Sea side was -0.10 μmol m^{-2} s^{-1} ($\pm$0.1 s.d.) using the sign convention of positive fluxes into the atmosphere from the ocean. pCO_{2sw} in the Beaufort Sea and the Elson Lagoon was relatively higher in early summer and decreased in the middle of the summer. The overall average CO_2 flux was -0.07 μmol m^{-2} s^{-1} ($\pm$0.1 s.d.) for the Beaufort Sea side and -0.03 μmol m^{-2} s^{-1} ($\pm$0.07 s.d.) for the Elson Lagoon respectively, indicating a sink of CO_2 despite high carbon inflows from the terrestrial margin into the Elson Lagoon. A strong sink of CO_2 was often observed from the Beaufort Sea by eddy covariance in the middle of the summer. This sink activity in the middle summer in the Beaufort Sea and Elson Lagoon was likely due to biological carbon uptake as inferred by low apparent oxygen utilization and high chlorophyll concentration that offset a potential source of CO_2 due to terrestrial carbon inputs.

1. Introduction

Climate change will affect the feedbacks by the Arctic Ocean at the regional and global scales (Semiletov et al., 2004). This is clear as in the case of effects of reductions in the Arctic sea ice extent and duration on the regional Albedo and energy balance (Holland and Bitz, 2003; Comiso et al., 2008). Less well studied are the effects of climate change on CO_2 flux over the Arctic Ocean (Bates and Mathis, 2009). It is well known that the terrestrial margin near the Arctic Ocean has a huge potential for positive feedbacks to climate change through increased net releases of greenhouse gases due to the large carbon reservoirs in the active layers and permafrost of these regions (Post et al., 1982; Miller et al., 1983). Arctic warming has a potential to alter the export of water, carbon and nutrients from the land draining into the Arctic Ocean, and, hence, the metabolism of net greenhouse gas budgets of the Arctic Ocean (Bates and Mathis, 2009). Global warming also likely decreases the Arctic sea ice extent and increases water temperature, which can both affect the net CO_2 balance of the Arctic Ocean (Bates et al., 2006). Formation and loss of sea ice directly influence carbon chemistry in seawater and the gas transfer velocity (Anderson et al., 2004; Rysgaard et al., 2007; Loose et al., 2011) and indirectly influence carbon exchanges through biological activities (Ikawa and Oechel, 2011; Loose et al., 2011). The land–sea interactions can be especially strong over coastal margins where the impact of salinity, water temperature, and organic and inorganic carbon inputs can be the greatest (Gattuso et al., 1998; Chen and Borges, 2009). To better

* Corresponding author. International Arctic Research Center, University of Alaska, 930 Koyukuk Dr., PO Box 757340, Fairbanks, AK 99775-7340, USA.
E-mail address: hikawa.biomet@gmail.com (H. Ikawa).

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predict future climate systems, it is necessary to quantify current carbon budgets and evaluate the environmental influences on air-sea CO_2 exchange (CO_2 flux) of the Arctic coastal ecosystems.

Understanding of the carbon exchange in the Arctic Ocean, including the western Arctic coastal shelf, has improved in recent years (Anderson et al., 1998; Murata and Takizawa, 2003; Semiletov et al., 2007; Bates and Mathis, 2009). The western Arctic coast is characterized by an inflow shelf where relatively nutrient rich water from the North Pacific flows in, and thus the shelf is likely a sink of CO_2 because of both biological and physical factors (Bates and Mathis, 2009). Seawater entering on to the Arctic shelf is cooled rapidly, thereby increasing the solubility of CO_2 gases. According to the general circulation model, HadCM3L ocean GCM (Yool and Fasham, 2001), extensive coastal shelves around the Bering Strait are likely favorable to the continental shelf pump, where sequestrated carbon within the continental shelf is transported to the subsurface layer of the open ocean by isopycnal mixing (Tsunogai et al., 1999). Sea ice is generally inhabited by ice algae (Quillfeldt et al., 2003; Ambrose et al., 2005), and their release to the water surface further enhances biological uptake of CO_2 (Horner and Schrader, 1982; Gosselin et al., 1997). As a result, partial pressure of surface seawater (pCO_{2sw}) in the high latitude is often lower than the atmospheric CO_2 pressure resulting in a local sink of CO_2 (Murata and Takizawa, 2003; Semiletov et al., 2004; Ikawa and Oechel, 2011). This low pCO_{2sw} is also attributed to the fact that seawater discriminates against dissolved inorganic carbon during the ice formation and that the CO_2 saturation concentration in water increases as seawater is cooled by the proximity of sea ice. $CaCO_3$ dissolution in spring further decreases pCO_{2sw} (Delille et al., 2007; Dieckmann et al., 2008; Miller et al., 2011). A part of the discriminated carbon during the ice formation is likely released to the atmosphere (Nomura et al., 2006), and $CaCO_3$ precipitation during the formation of ice within the ice pack may increase pCO_{2sw}. Thus, the information from the past studies revealed a typical seasonal pattern of CO_2 flux in the western Arctic coastal seas being a sink in spring to summer and a possible source in fall.

CO_2 flux over the Arctic coastal sea is also influenced by terrestrial inputs (Kling et al., 1991; Semiletov et al., 2011). In the Arctic coastal areas, a huge stock of organic carbon has been eroded into the coastal ocean, and the input of carbon into the aquatic systems is potentially a significant source of CO_2 offsetting a typical terrestrial sink during the summer growing season by 20% (Kling et al., 1991). Thus, inner estuaries, lagoons, and riverine systems tend to be a source of CO_2 to the atmosphere (Kelley, 1970; Kling et al., 1991; Frankignoulle et al., 1998; Wang and Cai, 2004; Semiletov et al., 2007, 2011, 2013; Koné et al., 2009; Anderson et al., 2011; Pipko et al., 2011), while offshore waters on the continental shelves are often a sink of CO_2 (Anderson et al., 1998; Tsunogai et al., 1999; Murata and Takizawa, 2003; Kaltin and Anderson, 2005). Therefore, to determine a regional air-sea CO_2 exchange of the Arctic coastal seas, it is necessary to evaluate CO_2 flux of the nearshore water with different extents of the terrestrial influences.

The study reported covers areas that include the inflow of shelf water mixing with turbid water with a strong terrestrial influence right off the tip of Point Barrow, Alaska. The west coast is adjacent to the Chukchi Sea, which is relatively less impacted by terrestrial inputs due to the strong water flow of the Alaskan Coastal Current. The northeast coast faces the Elson Lagoon where the water is stagnant and an influence of terrestrial carbon sources is expected to be much higher than the west coast. Significant amounts of coastal erosion have been reported near Point Barrow and the extent is the most prominent along the coast facing to the Elson Lagoon among our study sites (Hume et al., 1972; Brown et al., 2003). Thus, this region has an advantage for coastal studies allowing easy measurements of the contrasting situations with respect to the inflow shelf water that is relatively well mixed with outer water and the water with a great terrestrial influence. Additionally, this region has a long history of science and science supports by the local residents and a strong baseline and background of relevant scientific studies (Oechel et al., 2000; Kwon et al., 2006; Zona et al., 2009, 2011; Olivas et al., 2010; Goswami et al., 2011; Zulueta et al., 2011). Ikawa and Oechel (2011) and Semiletov et al. (2007) reported temporal variations in pCO_{2sw} of the coast of the Chukchi Sea within the study area.

Despite the extensive baseline data in this region, the impact of terrestrial ecosystems on coastal air-sea fluxes in the area has not been investigated. This is partly due to the fact that the western side of Point Barrow that was investigated by Ikawa and Oechel (2011) and Semiletov et al. (2004, 2007), is relatively less impacted by terrestrial inflows due to the strong Alaskan Coastal Current along the shore compared to the northeastern side that faces the Beaufort Sea and the Elson Lagoon. To adequately estimate sink and source balance of the nearshore water at the regional scale, it is necessary to observe temporal and spatial variations in CO_2 flux of both the western and northeastern sides of Point Barrow. Therefore, the objective of this study is to quantify CO_2 flux of alongshore water near Barrow, Alaska and compare the patterns of their temporal and spatial variability that would particularly differ between the western and northeastern sides of Point Barrow. To approach the objective, CO_2 flux was measured by eddy covariance and estimated by the bulk method using pCO_{2sw} data for the nearshore water and the temporal and spatial variations of CO_2 flux were evaluated with the variations of environmental factors (sea surface temperature (SST), salinity, apparent oxygen utilization (AOU), and chlorophyll concentration).

2. Methods

2.1. Site descriptions

Coastal seas near Barrow, Alaska are characterized by the Chukchi Sea off the west coast, the Beaufort Sea off the northeast coast, and the Elson Lagoon delineated by a strip of small barrier islands split off the northeast of Point Barrow (Fig. 1). The Alaskan Coastal Current flows along the west coast of Barrow from the North Pacific to the Chukchi Sea Shelf through the Bering Strait. This inflow shelf water in the Arctic coastal seas generally has a high primary productivity (Bates and Mathis, 2009), and low pCO_{2sw} was observed associated with high chlorophyll concentration within the study site in early summer of 2008 from a stationary measurement of pCO_{2sw} (Ikawa and Oechel, 2011). The Alaskan Coastal Current deflects eastward as it enters into the Barrow Canyon and flows toward the east in the Beaufort Sea. The deflection of the Alaskan Coastal Current occurs on further north, and our study site in the Beaufort Sea is not on the main path of the current. The flow rate of the Alaskan Coastal Current is particularly accelerated by easterly winds (Okkonen et al., 2009), and the rate significantly affects the heat balance of the Arctic Ocean (Shimada et al., 2006). There was no noticeable pattern within water current in our study area of either the Beaufort Sea or the Elson Lagoon.

The intertidal area of the west coast facing to the Chukchi Sea is covered with beach sands adjacent to a few residential areas, whereas eroded peat soils dominated by wet sedge tundra are exposed to the Elson Lagoon on the northeast side. Visually noticeable coastal erosion has been evident in the northeast coastline (Hume et al., 1972; Brown et al., 2003), and the amount of coastal sediment eroded into the lagoon is estimated to be 1.6×10^3 m^3 km^{-1} of coastline annually (Brown et al., 2003). A few river mouths reside in the northeastern side and runoffs directly

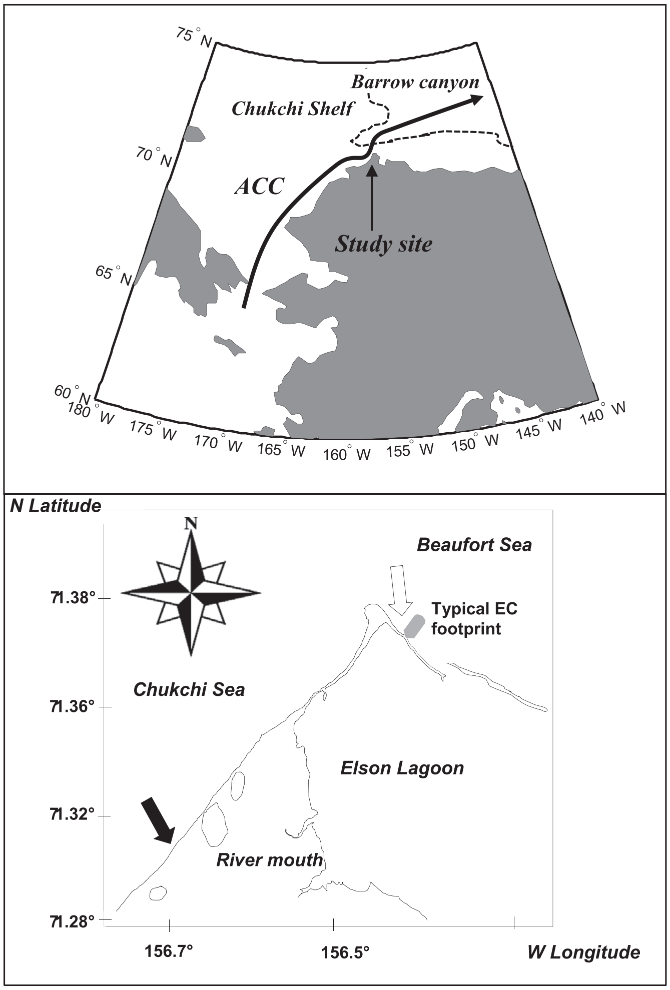

Fig. 1. Study sites near Barrow, Alaska. On the map above, the black arrow indicates a typical path of the Alaskan Coastal Current (ACC). On the map below, the white arrow (N71°22′4″, W156°25′5″) indicates the location where the eddy covariance measurements were conducted from June 26 to August 21, 2008, and the black arrow indicates the location where the stationary pCO_{2sw} measurement was conducted by Ikawa and Oechel (2011). The gray shadow indicates an approximate typical footprint.

flow into the Elson Lagoon. The amount of sediment carried by the riverine system in our study site was estimated to be about one seventh of the amount carried by erosion (Reimnitz et al., 1988). Some water in the Elson Lagoon was draining out to the Beaufort Sea through discontinuous sand strips at the northeast of Point Barrow.

The coastal sea of the study area was completely covered with landfast ice until the middle of June in 2007 and 2008. The landfast ice started breaking loose rapidly in the end of June and completely melted or drifted away offshore in the second week of July in the both years. Stormy weather came in August 1–7, 2008 and brought ice floes back to the shore, but the ice floes drifted away offshore again and became invisible from the shore in a few days. Predominant winds were from northeast, and the weather was overcast during the most of our measurement period.

2.2. Measurements

2.2.1. Boat-based measurements

pCO_{2sw}, SST, and salinity were measured underway from August 2 to 7 and on September 11 in 2007 and from July 10 to August 21 in 2008 whenever the weather conditions allowed a safe operation of the equipment (typically wind speed was less than 5 m s^{-1}). Dissolved oxygen and chlorophyll concentration measurements were added in 2008. Because we needed to stop cruising for about 10 min to measure chlorophyll concentration accurately, the measurement was limited to 5 times (July 14, July 27, July 28, August 7, and August 18) in the Chukchi Sea side, 4 times (July 27, July 28, August 6, and August 18) in the Beaufort Sea side, and 4 times (July 27, July 28, August 11, and August 21) in the Elson Lagoon sites. The time and the course of each cruise were primarily determined by weather and sea conditions for safety.

The pCO_{2sw} measurements were performed by a headspace method (Ikawa and Oechel, 2011). The headspace equilibrator was attached to the side of a boat, and the water intake was no more than 20 cm deep from the water surface. The sample air in the headspace was continuously introduced into the detector cell of an infrared gas analyzer (LI-840; LI-COR Biosciences, USA) to measure CO_2 concentration in the headspace. The CO_2 concentration in the water vapor-saturated headspace at the equilibrator temperature was converted to pCO_{2sw} with respect to pressure of the equilibrator which was maintained at the ambient atmospheric pressure with a pressure buffer tube. The temperature in the equilibrator was higher than SST by about 0.3 °C, and the temperature difference was corrected with the Takahashi et al. (1993)'s pCO_{2sw} − temperature relation. Atmospheric pressure data were obtained from a weather station located a half mile inland from the coast at the Global Monitoring Division (GMD) of the Climate Monitoring and Diagnostics Laboratory (CMDL). The atmospheric pressure data were not available before July 27, 2008, and the overall average pressure used after July 27, 2008 was used for the measurement before July 27, 2008. The effect of the variation in atmospheric pressure on pCO_{2sw} was minimal as the difference in atmospheric pressure changed pCO_{2sw} by 1.8% at most. Atmospheric CO_2 concentration was also measured with the same detector periodically with an air intake attached near the top of a 3 m long pole mounted on the boat, and converted to atmospheric CO_2 pressure (pCO_{2air}) with the atmospheric pressure data. The infrared gas analyzer was calibrated prior to each cruise.

SST, salinity, and dissolved oxygen were measured with a CTD (YSI600R; YSI Incorporated, USA) right next to the water intake for the pCO_{2sw} measurements. The CTD was calibrated with a conductivity calibrator (YSI 3169; YSI Incorporated, USA) for salinity and copper-constantan thermocouples for temperature immediately before the measurement season. The oxygen sensor was calibrated by the factory a few months prior to the measurement. Chlorophyll concentration was estimated with in situ measurements by a fluorometer (FLNTU; WET Labs, USA). The fluorometer was calibrated by the factory, WET Labs immediately before the measurement season. AOU was calculated by subtracting dissolved oxygen from the saturated oxygen concentration at given salinity and SST. We did not calibrate the CTD or fluorometer after the end of the measurement season, but there was no noticeable sensor drift during the measurements and maintenance after each cruise.

All the measurements except for the chlorophyll measurement were conducted underway. Each cruise was limited to at most 2 h to ensure the accurate reading of the LI-840 gas analyzer. Ikawa and Oechel (2011) reported that the diurnal variation of pCO_{2sw} observed at a fixed point within our study area in the Chukchi Sea was negligible compared to the day-to-day variation, and we assumed that pCO_{2sw} remained relatively constant over time during the each cruise.

2.2.2. Estimates of CO_2 flux from pCO_{2sw} data over summer in 2008

CO_2 flux (F_c, μmol m^{-2} s^{-1}) was calculated from pCO_{2sw} (C_{pw}, μatm), SST (°C), salinity (psu), and atmospheric CO_2 pressure, pCO_{2air} (C_{pa}, μatm) with the bulk method for each pCO_{2sw} measurement based on the following equation (e.g., Wanninkhof and McGillis, 1999).

$$F_c = \alpha\, k\left[C_{pa} - C_{pw}\right], \quad (1)$$

Solubility (α, mol m^{-3} atm^{-1}) was computed by SST and salinity based on Weiss (1974); the gas transfer velocity (k, m s^{-1}), was determined as an average of the gas transfer velocity following Wanninkhof (1992) and Sweeney et al. (2007). Wind speeds used to calculate k were obtained every 30 min from the CMDL weather station. To roughly estimate the total CO_2 flux over the summer in 2008, the bulk method was applied to pCO_{2sw} and the gas transfer velocity estimated every 30 min. When there was no pCO_{2sw} or solubility data corresponding to the gas transfer velocity, they were estimated to be the values observed at the closest time.

2.2.3. Eddy covariance measurements and data processing

Eddy covariance measurements of CO_2 flux were operated from June 26 to August 21 in 2008. Predominant winds from northeast allowed us to operate eddy covariance measurements only at the sand strip (N71°22′4″, W156°25′5″) located at the northeast side of Point Barrow facing the Beaufort Sea (Fig. 1).

A sonic anemometer (C-Sat; Campbell Scientific, USA) for three dimensional wind speeds and temperature and an open path infrared gas analyzer (LI-7500; LI-COR Biosciences, USA) for CO_2 and H_2O densities were mounted on a 2.5 m tower on the shore. The shore was elevated by about 0.5 m from the seawater surface. The area was covered with gravel and beach sands, and the horizontal distance between the sea front and the sensor in upwind direction was about 10 m. The density of CO_2, and H_2O, three dimensional wind components, and temperature were recorded at 10 Hz. The data were stored in a compact memory flash in the datalogger (CR1000; Campbell Scientific, USA) and manually extracted.

The computation of eddy covariance followed Ikawa et al. (2013). Data quality was assessed by (1) diagnostic values provided by the infrared gas analyzer and the sonic anemometer (26%: numbers in brackets indicate the data percentage filtered out by each process), (2) correlation coefficients of CO_2 mixing ratio and vertical wind speeds (Businger, 1986; Foken and Wichura, 1996; Reba et al., 2009) (22%), and (3) wind directions (55%). After these filtering processes, apparent outliers were filtered out based on the double-differenced time series, using the median of absolute deviation about the median (3%) (Sachs, 1996). The parameter z in the outlier detector was set at 4 (Papale et al., 2006). After filtering data, 19% of the total amount of data set for CO_2 flux was considered to have a reliable quality and used for further data analysis.

The LI-7500 gas analyzer provides the AGC (Automated Gain Control) value, which is an indicator of contamination levels on the sensor, and the C-sat anemometer provides a diagnostic value to report sensor malfunctions when they occur. Data were filtered out when the AGC value was higher than 250, or the diagnostic value of the anemometer indicated a sensor malfunction. Data were filtered out when the absolute value of the correlation coefficient of CO_2 mixing ratio or vertical wind speeds was less than 0.05. The absolute value of the average correlation coefficient of accepted data was 0.25. The correlation coefficient for the ocean flux has been reported poorly, but typical values observed for terrestrial ecosystems are 0.15–0.4 (Hicks, 1981; Businger, 1986; Kaimal et al., 1990; Reba et al., 2009). The data during offshore winds (when wind directions were 100°–330°) were filtered out from the analysis. The footprint analysis (Schuepp et al., 1990) showed the peak contribution along the upwind distance occurred at 80–90 m away from the tower.

3. Results

3.1. Temporal and spatial patterns in pCO_{2sw} and environmental parameters

pCO_{2sw} measured from the Chukchi Sea was lower than pCO_{2air} except for the measurement on August 18, 2008 resulting in the average pCO_{2sw} of 255 μatm (±79 s.d.) (Fig. 2). Low pCO_{2sw} below 200 μatm was observed in the Chukchi Sea side in the early seasons in both 2007 and 2008 (Fig. 2 (a), (e)–(g)). The lowest pCO_{2sw} of 150 μatm was observed in the Chukchi Sea side on July 17, 2008. pCO_{2sw} in the Chukchi Sea increased later in the season both 2007 and 2008 and became slightly higher than pCO_{2air} on August 18, 2008. Higher pCO_{2sw} than pCO_{2air} was often observed in the Elson Lagoon both in 2007 and 2008 (Fig. 2 (c), (h)), although the overall average pCO_{2sw} of 321 μatm (±61 s.d.) was lower than pCO_{2air}. pCO_{2sw} in the Elson Lagoon decreased at the end of the measurement season in 2008 (Fig. 2 (m), (o)). The amount of chlorophyll data was not enough to detect a temporal variation, but the intermittent measurement showed relatively higher chlorophyll concentration in the Elson Lagoon ranging from 0.13 to 1.47 μg kg^{-1}, while other areas ranged from 0.08 to 0. 45 μg kg^{-1} (Fig. 2).

SST was relatively lower in the Chukchi Sea side with the mean of 4.9 °C (±2.8 s.d.) than other areas with the mean of 6.7 °C (±1.9 s.d.) (data not shown). No apparent trend was found in the temporal variation of SST. Low salinity of (~10 psu) was observed along the coast on July 14 (Fig. 3 (f)) and in the Elson Lagoon on July 22 (Fig. 3 (h)) in 2008. The low salinity observed along the coast on July 14, 2008 was likely due to the diluted seawater after sea ice had melted, whereas the low salinity in the Elson Lagoon was likely due to freshwater inputs from lands. AOU in the Chukchi Sea side measured in July, 2008 was mostly negative indicating that the water was super-saturated with dissolved oxygen. AOU in the Chukchi Sea side dramatically increased after the first measurement on July 10, 2008. On the contrary to the increase trend of AOU in the Chukchi Sea, AOU in the Elson Lagoon decreased in the middle of summer in 2008 (Fig. 4 (h), (m), (o)). All the data from the boat-based measurements are summarized in Table 1.

3.2. Estimates of CO_2 flux from the pCO_{2sw} data in summer, 2008

pCO_{2sw} near the Barrow coast was mostly lower than pCO_{2air} of 360–380 μatm in the summer 2008, resulting in the overall sink of CO_2 of −0.10 μmol m^{-2} s^{-1} (±0.1 s.d.) from the Chukchi Sea side, −0.07 μmol m^{-2} s^{-1} (±0.1 s.d.) from the Beaufort Sea side and −0.03 μmol m^{-2} s^{-1} (±0.07 s.d.) from the Elson Lagoon side (Fig. 5). The lowest CO_2 flux calculated from the pCO_{2sw} data of down to −0.66 μmol m^{-2} s^{-1} was observed in the Chukchi Sea side owing to low pCO_{2sw} and high gas transfer velocity in the end of July. Sources of CO_2 were observed later in the measurement season in the Chukchi Sea side and earlier in the measurement season in the Elson Lagoon due to higher pCO_{2sw} than the pCO_{2air}.

3.3. CO_2 flux measured by eddy covariance

The overall average CO_2 flux was −0.2 (±1.5 s.d.) μmol m^{-2} s^{-1} showing a sink of CO_2 (Fig. 6). The sign of CO_2 flux frequently changed during the presence of the landfast ice and the value ranged from −2.5–2.0 μmol m^{-2} s^{-1}. A sink of CO_2 was observed more frequently later in the season after visually 80% of the footprint was ice-free. The highest CO_2 uptake of 5.8 μmol m^{-2} s^{-1} was observed in the midday on August 17.

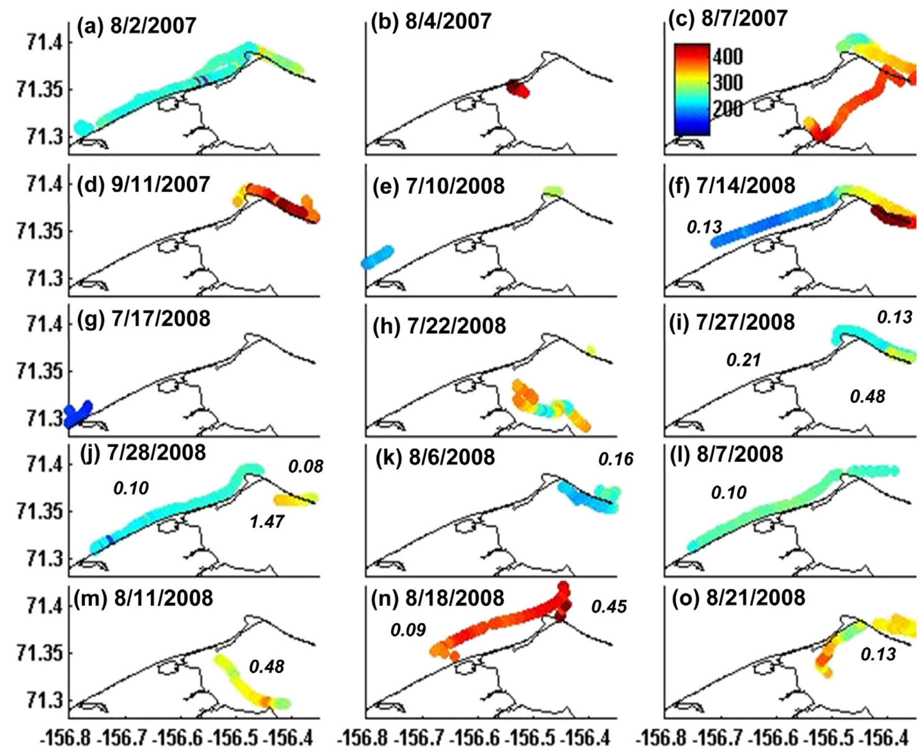

Fig. 2. Boat cruise measurements for the partial pressure of CO_2 of surface seawater (pCO_{2sw}) (μatm) measured for the nearshore water near Barrow, Alaska on (a) Aug 2, (b) Aug 4, (c) Aug 7, and (d) Sep 11, 2007 and (e) Jul 10, (f) Jul 14, (g) Jul 17, (h) Jul 22, (i) Jul 27, (j) Jul 28, (k) Aug 6, (l) Aug 7, (m) Aug 11, (n) Aug 18, and (○) Aug 21, 2008. The italic numbers show chlorophyll concentration (μg kg^{-1}) observed in situ.

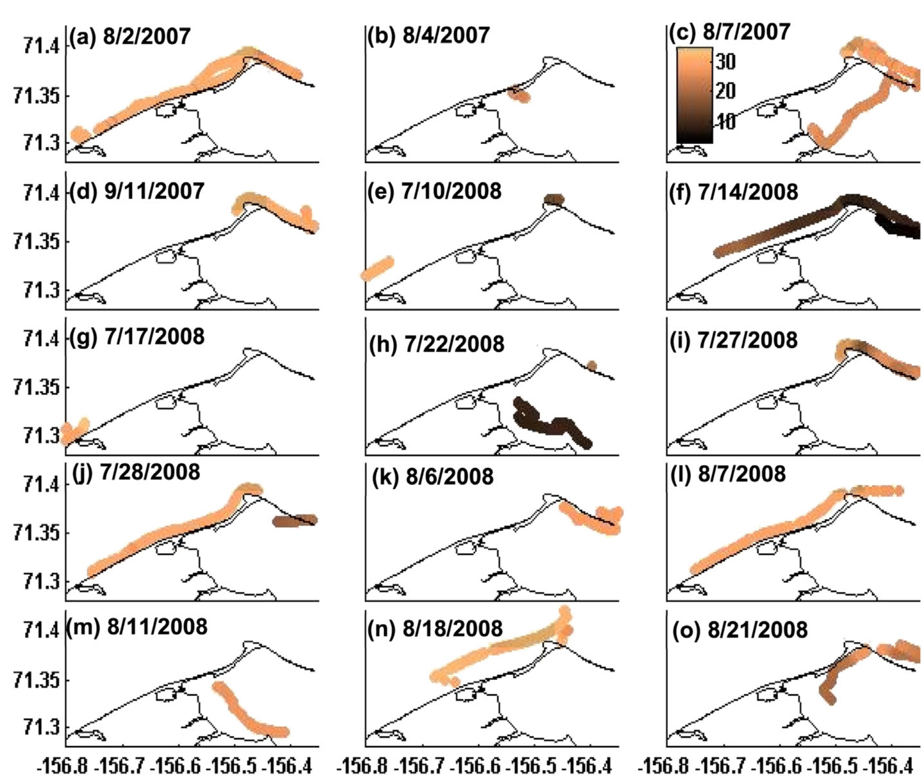

Fig. 3. Boat cruise measurements for salinity (psu) measured for the nearshore water near Barrow, Alaska on (a) Aug 2, (b) Aug 4, (c) Aug 7, and (d) Sep 11, 2007 and (e) Jul 10, (f) Jul 14, (g) Jul 17, (h) Jul 22, (i) Jul 27, (j) Jul 28, (k) Aug 6, (l) Aug 7, (m) Aug 11, (n) Aug 18, and (○) Aug 21, 2008.

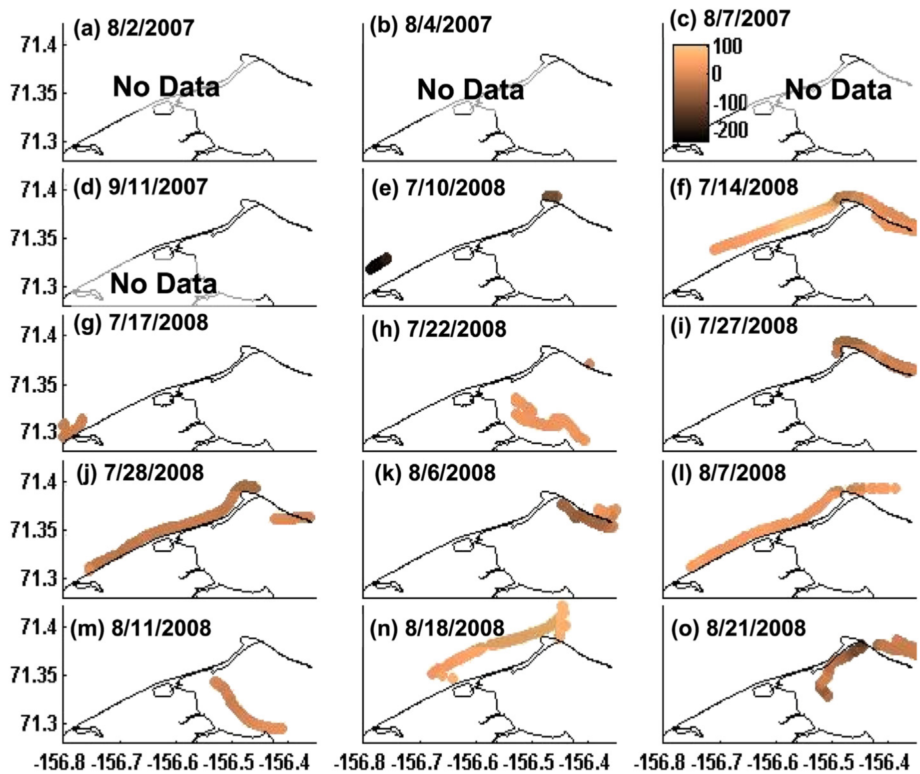

Fig. 4. Boat cruise measurements for apparent oxygen utilization (AOU) (μmol kg^{-1}) measured for the nearshore water near Barrow, Alaska on (a) Aug 2, (b) Aug 4, (c) Aug 7, and (d) Sep 11, 2007 and (e) Jul 10, (f) Jul 14, (g) Jul 17, (h) Jul 22, (i) Jul 27, (j) Jul 28, (k) Aug 6, (l) Aug 7, (m) Aug 11, (n) Aug 18, and (○) Aug 21, 2008.

4. Discussions

Contrasting differences in pCO_{2sw} and CO_2 flux were found between the Chukchi Sea side and in the Elson Lagoon. pCO_{2sw} was generally lower in the Chukchi Sea than the Elson Lagoon except for later in August, 2008. High pCO_{2sw} in the Elson Lagoon was likely due to terrestrial carbon inputs and relatively high SST. SST was higher in the Elson Lagoon than the Chukchi Sea by 2 °C on average, and the higher SST can thermodynamically increase pCO_{2sw} by 9% given the same water chemistry based on the Takahashi's pCO_{2sw} − temperature relation (Takahashi et al., 1993). The lower temperature in the Chukchi Sea side was likely due to higher water circulations induced by the Alaskan Coastal Current.

Although observed pCO_{2sw} was occasionally higher than pCO_{2air} in the Elson Lagoon, the area was a sink of CO_2 on average during the measurement. Brown et al. (2003) estimated organic carbon transport due to erosion from the terrestrial margin to the Elson Lagoon to be 6×10^4 kg C km^{-1} $year^{-1}$, and additionally about a seventh of organic carbon is estimated to be drained from rivers. This total carbon input is roughly equivalent to about 0.1 μmol m^{-2} s^{-1} of CO_2 efflux if all of the terrestrially derived organic carbon was completely remineralized and transported to the atmosphere within the Elson Lagoon during the ice free season, if one can assume that the cross-shore distance of the Elson Lagoon is 8 km. Note that soil carbon content in the high northern latitude considerably varies spatially (Tarnocai et al., 2009), and the estimate of the carbon transport is sensitive to soil organic carbon content to be determined. The CO_2 efflux of 0.1 μmol m^{-2} s^{-1} is equivalent to 20% of carbon sink per unit area in the adjacent wet sedge tundra in the summer growing season (Kwon et al., 2006). The suppression of a CO_2 release to the atmosphere in the Elson Lagoon in spite of the terrestrial carbon inputs is likely due to high biological carbon uptake in the Elson Lagoon inferred by high chlorophyll concentration and low to negative AOU often observed later in summer (Figs. 2 and 4). At the Buor-Khaya Bay near the Laptev Sea where biological carbon uptake is considered low due to very low transparency of water, the degradation of organic carbon transported by coastal erosion and river discharge characterizes high pCO_{2sw} of up to 4000 μatm (Semiletov et al., 2013), which results in the CO_2 efflux of 3 μmol m^{-2} s^{-1}, if the same parameters were to be used for the CO_2 flux calculation as for the Elson Lagoon with Eq. (1). Despite the sink of CO_2 in the Elson lagoon, biologically sequestrated carbon is most likely released back to the atmosphere if the carbon is not transported to the depth of the ocean (e.g., Semiletov et al., 2011). Therefore, the fate of carbon, particularly, of organic carbon needs to be studied for a further understanding of CO_2 flux of the nearshore water where terrestrial inputs are high.

Temporal patterns of pCO_{2sw} and CO_2 flux differed between the eastern and western sides off the Barrow coast. pCO_{2sw} in the Chukchi Sea side showed an increasing trend over time both in 2007 and 2008, and became slightly higher than pCO_{2air} on August 11, 2008. The increasing trend of pCO_{2sw} in the Chukchi Sea side was also confirmed by the stationary pCO_{2sw} system that was operated from June to August in 2008 (Ikawa and Oechel, 2011). Low pCO_{2sw} of the nearshore water of the Chukchi Sea is likely attributed to relatively CO_2-free water from melting sea ice and a biological carbon uptake by ice algae (Semiletov et al., 2004; Ikawa and Oechel, 2011). Although there was no ice in the study area after the second week of July 2008, pCO_{2sw} was kept low until the nearshore water was well mixed with the water offshore. The temporal variation of pCO_{2sw} in the Elson Lagoon was likely influenced by the local biological activity that resulted in low pCO_{2sw} corresponding to low AOU and high chlorophyll concentration. The sinks of CO_2 observed by eddy covariance for the Beaufort Sea during the ice-free period were most likely due to the local

Table 1
Summary of the boat cruise measurements for the Chukchi Sea side (CS), the Beaufort Sea side (BS), and the Elson Lagoon (EL) near Point Barrow, Alaska in summer 2007 and 2008.

Cruise date	Atmospheric pressure	pCO_{2atm}	pCO_{2sw} (µatm)			SST (°C)		
	(atm)	(µatm)	CS	BS	EL	CS	BS	EL
2-Aug-07	–	360	242 (20)	284 (23)	–	7.8 (0.15)	8.8 (0.43)	–
4-Aug-07	–	376	–	–	430 (19)	–	–	8.7 (0.2)
7-Aug-07	–	358	261 (13)	332 (21)	388 (17)	9.3 (0.19)	8.9 (0.22)	9.6 (0.14)
11-Sep-07	–	379	325 (14)	393 (32)	–	8.8 (0.21)	6.2 (0.43)	–
10-Jul-08	–	371	202 (6)	291 (9)	–	−1.2 (0.17)	4.4 (0.09)	–
14-Jul-08	–	369	195 (14)	305 (23)	423 (32)	3.6 (1.12)	6.6 (0.59)	8.3 (0.33)
17-Jul-08	–	363	159 (3)	–	–	1.7 (0.15)	–	–
22-Jul-08	–	377	–	–	321 (43)	–	–	6.0 (0.15)
27-Jul-08	0.997	369	235 (4)	233 (10)	291 (9)	6.3 (0.52)	6.8 (0.35)	6.5 (0.53)
28-Jul-08	0.992	370	237 (17)	248 (2)	321 (10)	5.5 (0.13)	5.7 (0.12)	7.8 (0.34)
6-Aug-08	1.009	372	–	251 (12)	214 (17)	–	3.2 (0.56)	3.6 (0.06)
7-Aug-08	1.01	370	262 (9)	245 (12)	–	4.3 (0.24)	3.3 (0.80)	–
11-Aug-08	1.004	367	–	–	308 (18)	–	–	7.0 (0.14)
18-Aug-08	1.006	370	393 (17)	430 (33)	–	1.2 (0.47)	3.4 (1.4)	–
21-Aug-08	1.003	361	–	332 (8)	326 (28)	–	5.7 (0.17)	6.6 (0.73)

Cruise date	Salinity (psu)			AOU (µmol kg^{-1})			Chlorophyll concentration (µg kg^{-1})		
	CS	BS	EL	CS	BS	EL	CS	BS	EL
2-Aug-07	30.5 (0.8)	28.2 (1.2)	–	–	–	–	–	–	–
4-Aug-07	–	–	25.7 (1.1)	–	–	–	–	–	–
7-Aug-07	28.4 (1.7)	27.7 (1.5)	25.4 (0.5)	–	–	–	–	–	–
11-Sep-07	31.3 (0.04)	30.2 (1.0)	–	–	–	–	–	–	–
10-Jul-08	31.2 (0.1)	17.1 (0.9)	–	−222 (12)	−70 (8)	–	–	–	–
14-Jul-08	14.2 (2.8)	9.5 (0.5)	5.1 (1.5)	48 (29)	10 (8)	20 (4)	0.13 (0.1)	–	–
17-Jul-08	30 (0.8)	–	–	−16 (3)	–	–	–	–	–
22-Jul-08	–	–	8.8 (1.1)	–	–	22 (3)	–	–	–
27-Jul-08	26 (4.5)	24 (1.4)	23 (1.4)	−26 (4)	−14 (13)	−10 (3)	0.21 (0.2)	0.13 (0.08)	0.48 (0.2)
28-Jul-08	29.9 (0.5)	29.8 (0.2)	19.5 (0.87)	−21 (8)	−18 (1)	−2 (4)	0.1 (0.1)	0.08 (0.05)	1.47 (0.08)
6-Aug-08	–	28.3 (0.1)	28.2 (0.1)	–	18 (14)	−52 (21)	–	0.16 (0.2)	–
7-Aug-08	29.4 (0.2)	28.3 (1.0)	–	27 (8)	33 (9)	–	0.1 (0.1)	–	–
11-Aug-08	–	–	27.1 (0.21)	–	–	−3 (10)	–	–	0.48 (0.7)
18-Aug-08	31.6 (0.5)	29.9 (2.6)	–	56 (16)	72 (7)	–	0.09 (0.09)	0.45 (0.2)	
21-Aug-08	–	27.9 (0.1)	22.7 (2.6)	–	−11 (5)	−37 (28)	–	–	0.13 (0.07)

biological uptake of CO_2 rather than the seasonal trend that is generally observed elsewhere in the Arctic nearshore water.

CO_2 flux measured by eddy covariance for the Beaufort Sea showed high temporal variation. While CO_2 flux estimated by eddy covariance ranged from −5.8 to +2.0 µmol m^{-2} s^{-1}, CO_2 flux estimated by the bulk method ranged from −0.66 to +0.16 µmol m^{-2} s^{-1} showing that the temporal variation was several times higher in eddy covariance than the bulk method. The difference of the magnitude of the temporal variation may have attributed to the fact that eddy covariance has a higher temporal resolution, and uncertainty of the bulk method in determining the gas transfer velocity. Sea ice, particularly first-year sea ice has been reported to be permeable to CO_2 gas (Miller et al., 2011; Papakyriakou and Miller, 2011). Laboratory tests and field observations have shown a substantial gas transfer through factures of sea ice, and the gas transfer is likely underestimated if a wind-driven mixing was assumed to be the most influential parameter (Gosink et al., 1976; Else et al., 2011; Loose et al., 2011). A challenge still remains in accurate quantification of the gas transfer in the presence of sea ice.

The study area was limited to the nearshore water off Point Barrow; however, the area likely represents much larger regions of the coastal water of the western Arctic Ocean. The study area in the Chukchi Sea was spatially less variables in pCO_{2sw} as well as other parameters (Figs. 2–4, Table 1) due to the strong water flow of the Alaskan Coastal Current. Low pCO_{2sw} observed during the ice melting season is similarly expected in the extensive area of the Arctic coast partly, but strongly due to high primary productivity, which would result in a significant amount of carbon uptake from the continental shelf water in the Arctic (Anderson and Jones, 1991; Walsh, 1991). The shelf water loses productivity after the ice melting season as inferred by high AOU and low chlorophyll concentration in the Chukchi Sea side in the later season (Figs. 2 and 5, Table 1). Murata and Takizawa (2003) surveyed pCO_{2sw} along the extensive transect on the Chukchi Sea Shelf from near the Bering Strait to the deep water off the shelf in the late summer in 1998–2000 to find that pCO_{2sw} measured on the shelf was controlled by temperature with little to no biological activity. Cooper et al. (1997) reported that nutrient concentrations significantly declined during the course of the north-flow water from the North Pacific to the western Arctic continental shelf as a consequence of biological utilization and dilution with nutrient-poor freshwater in summer.

The similar geographical feature to the northeastern side of our study site is existent in the extensive coastal line in the northeastern side of the Alaskan coast facing to the Beaufort Sea with fragile soil fractured and exposed to the waterfront. Significant coastal erosion has been reported elsewhere from this extensive coastal line (Jorgenson et al., 2003; Jones et al., 2008). Jorgenson et al. (2003) estimated the annual carbon inflow at about 200 km east from our study site to be 37,800–68,000 kg C km^{-1} year^{-1}, which is similar to the amount reported from near our study site (Brown et al., 2003). Our study suggests a possibility that the

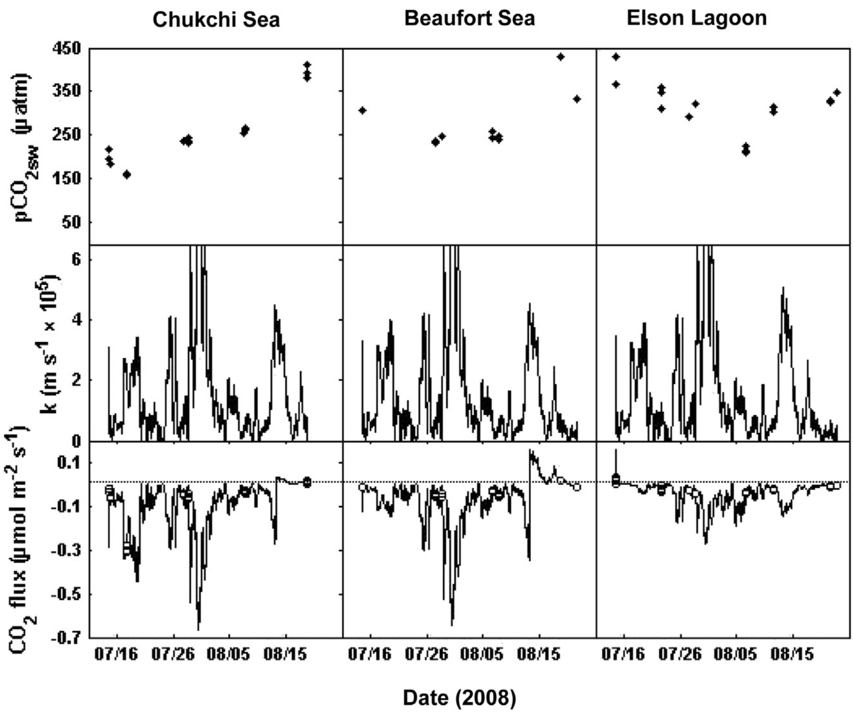

Fig. 5. Average pCO_{2sw} measured at each cruise for the nearshore water of the Chukchi Sea, Beaufort Sea, and the Elson Lagoon near Barrow Alaska (top panels), gas transfer velocity, *k* (middle panels), and CO_2 flux estimated based on pCO_{2sw} and *k* (bottom panels). Gas transfer velocity, *k* was determined as an average of two values calculated following Wanninkhof (1992) and Sweeney et al. (2007). pCO_{2sw} was linearly interpolated to calculate CO_2 flux corresponding to each *k*.

extensive coastal water facing to the Beaufort Sea can be a sink of CO_2 locally due to biological uptake, although the nearshore water in the Arctic is a source of CO_2 in general (Kling et al., 1991; Semiletov et al., 2011, 2013). Further investigations are necessary for the area to evaluate the extent of the local biological uptake and the fate of the sequestered carbon.

5. Conclusion

Spatial and temporal variability of pCO_{2sw} and CO_2 flux were examined in the coastal water near Barrow Alaska in summer, 2007 and 2008. Contrasting differences were found in the temporal patterns of pCO_{2sw} and CO_2 flux between the western side of Barrow facing to the Chukchi Sea and the northeastern side that faces to the Elson Lagoon. Measured pCO_{2sw} in the Chukchi Sea side was the lowest in the beginning of the measurement season and increased after the sea ice melting season. The temporal trend likely represents a large area of the continental shelf water on the Chukchi Sea Shelf. Although pCO_{2sw} in the Elson Lagoon was often higher than pCO_{2air}, the area was a sink of CO_2 on average due to local biological carbon uptakes. The eddy covariance data also showed sinks of CO_2 occurred frequently in the Beaufort Sea in the middle of the summer. Our study suggests that the extensive nearshore water along the Beaufort Sea can be a sink of CO_2 locally, despite high terrestrial carbon inflows. A further investigation is necessary to evaluate the extent of biological uptake that occurs locally and the fate of the sequestered carbon in the nearshore water of the Beaufort Sea where the carbon inflows from the terrestrial margin may compose a large fraction of the carbon cycle in the Arctic Ocean.

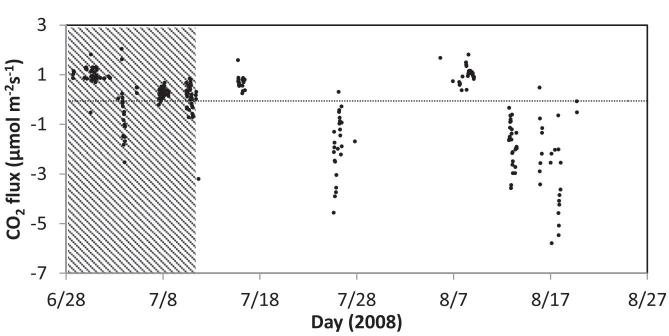

Fig. 6. CO_2 flux measured by eddy covariance for the nearshore water of the Beaufort Sea (N71°22′4″, W156°25′5″) near Point Barrow, Alaska in 2008. The shadows indicate the period when more than 80% of the footprint was visibly covered with ice (June 28 – July 11).

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