



## 1    **The importance of freshwater systems to the net exchange of 2    atmospheric carbon dioxide and methane with rapidly changing 3    high Arctic landscapes**

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10    **Abstract.** A warming climate is rapidly changing the distribution and exchanges of carbon within high Arctic  
11    ecosystems. Few data exist, however, which quantify exchange of both carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>)  
12    between the atmosphere and freshwater systems, or estimate freshwater contributions to total catchment exchange of  
13    these gases, in the high Arctic. During the summers of 2005 and 2007-2012, we quantified CO<sub>2</sub> and CH<sub>4</sub>  
14    concentrations in, and atmospheric exchange with, common freshwater systems in the high Arctic watershed of Lake  
15    Hazen, Nunavut, Canada. We identified four types of biogeochemically-distinct freshwater systems in the  
16    watershed, however mean CO<sub>2</sub> concentrations (21–28  $\mu\text{mol L}^{-1}$ ) and atmospheric exchange (-0.013–0.046 g C-CO<sub>2</sub>  
17     $\text{m}^{-2} \text{ d}^{-1}$ ) were similar between these systems. Seasonal flooding of ponds bordering Lake Hazen generated  
18    considerable CH<sub>4</sub> emissions to the atmosphere (0.008 g C-CH<sub>4</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ), while all other freshwater systems were  
19    minimal emitters of this gas (<0.001 g C-CH<sub>4</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ). Measurements made on terrestrial landscapes in the same  
20    watershed between 2008-2012 determined that the near-barren polar semidesert was a very weak consumer of  
21    atmospheric CO<sub>2</sub> (-0.004 g C-CO<sub>2</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ), but an important consumer of atmospheric CH<sub>4</sub> (-0.001 g C-CH<sub>4</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ).  
22    Alternatively, meadow wetlands were very productive consumers of atmospheric CO<sub>2</sub> (-0.96 g C-CO<sub>2</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ) but  
23    relatively weak emitters of CH<sub>4</sub> to the atmosphere (0.001 g C-CH<sub>4</sub>  $\text{m}^{-2} \text{ d}^{-1}$ ). When using ecosystem-cover  
24    classification mapping, we found that freshwaters were unimportant contributors to total watershed carbon  
25    exchange, in part because they covered less than 10% of total cover in the watershed. High Arctic watersheds are  
26    experiencing warmer and wetter climates than in the past, which may have implications for the net uptake of carbon  
27    greenhouse gases by currently underproductive polar semidesert and freshwater systems.

28    **Keywords:** carbon dioxide, methane, lake, pond, high Arctic, climate change, watershed



29 **1 Introduction**

30 Freshwater ecosystems cover less than 10% of global ice-free land area (Lehner and Doll, 2004) and have  
31 been typically overlooked as substantial contributors to, or sinks of, atmospheric carbon greenhouse gases (GHGs;  
32 Bastviken et al., 2011). However, recent studies suggest inland lakes collectively receive and process carbon at  
33 magnitudes similar to oceanic uptake and sediment burial, making them important systems within the global carbon  
34 cycle (Cole et al., 2007; Battin et al., 2009; Tranvik et al., 2009; Maberly et al., 2013; Raymond et al., 2013).  
35 Though these lowland systems efficiently accumulate allochthonous and autochthonous carbon, most natural lakes  
36 and ponds, on balance, emit carbon GHGs to the atmosphere. For example, in most freshwater ecosystems,  
37 decomposition continuously adds carbon dioxide (CO<sub>2</sub>) to the water before venting to the atmosphere (Rautio et al.,  
38 2011), while uptake of CO<sub>2</sub> by autotrophs occurs typically over shorter seasonal periods (Cole et al., 2000; Huttunen  
39 et al., 2003; Breton et al., 2009; Bastviken et al., 2011; Rautio et al., 2011; Callaghan et al., 2012). At the same time,  
40 lake sediments and even oxic waters can sustain bacterial methanogenesis and the production of the potent GHG  
41 methane (CH<sub>4</sub>; Bogard et al., 2014). Due to the gas's poor solubility in water, ebullition and wind can then  
42 efficiently vent CH<sub>4</sub> to the atmosphere from these ecosystems, perhaps contributing up to 12% of global emissions  
43 (Lai, 2009; Walter et al., 2006).

44 Lakes, ponds and wetlands are globally most abundant in northern regions, largely due to past periods of  
45 glaciation and resulting land deformation. These freshwater environments may cover greater than half the landscape  
46 in northern regions, and can account for more than three-quarters of a landscape's net CO<sub>2</sub> exchange with the  
47 atmosphere (Abnizova et al., 2012). Saturated northern peatlands can also be robust emitters of CH<sub>4</sub> because  
48 permafrost impedes drainage of soils, promoting anoxia and methanogenesis (Tagesson et al., 2012; Wik et al.,  
49 2016). However, at the highest northern latitudes (>70°N), polar semidesert landscapes not covered by glaciers  
50 generally have cold, relatively well-drained soils (Campbell and Claridge, 1992) and receive little precipitation,  
51 resulting in often less than 5% of the landscape being covered by aquatic systems. Though easy to overlook as  
52 sparsely-vegetated barrens that exchange few carbon GHGs with the atmosphere (Soegaard et al., 2000; Lloyd,  
53 2001; Lund et al., 2012, Lafleur et al., 2012), recent studies have shown that where conditions are ideal, high Arctic  
54 ecosystems exchange GHGs at rates similar to ecosystems at more southerly latitudes (Emmerton et al., 2014;  
55 Emmerton et al., 2016).



56                   High Arctic ecosystem productivity is currently changing rapidly as a warming climate substantially alters  
57                   polar watersheds (IPCC, 2007a). Some climate models predict that in the Canadian Arctic, autumn and winter  
58                   temperatures may rise 3-5°C by 2100, and up to 9°C in the high Arctic (>70°N; ACIA, 2004; IPCC, 2007b). Mean  
59                   annual precipitation is projected to increase ~12% for the Arctic as a whole over the same period, and up to 35% in  
60                   localized regions where the most warming will occur (ACIA, 2004; IPCC, 2007b). Such warming and wetting is  
61                   already modifying Arctic landscape energy balances (Froese et al., 2008) resulting in glacial melt (Pfeffer et al.,  
62                   2008), permafrost thaw (Peterson et al., 2002), reorganized hydrological regimes (i.e., drying or wetting; Smith et  
63                   al., 2008) and extended growing seasons (Manabe et al., 1994). These changes are also perturbing watershed carbon  
64                   cycling through, for example, the liberation of carbon from thawing permafrost, and increases in biological  
65                   productivity on landscapes and in lakes, ponds and wetlands (Mack et al., 2004; Smol et al., 2005; Walker et al.,  
66                   2006; Smol and Douglas, 2007). Considering the extensive cover of the near-barren polar semidesert in the high  
67                   Arctic (>10<sup>6</sup> km<sup>2</sup>), these changes may have considerable effects on the future net exchange of carbon GHGs both  
68                   locally and on a global scale (Anthony et al., 2014). However, climate changes are far better delineated and  
69                   predicted for high Arctic landscapes in general than specifically for freshwater systems and landscape-scale GHG  
70                   exchange with the atmosphere. Therefore it is uncertain how rapid climate change will alter the cycling of carbon in  
71                   these remote regions.

72                   The primary objective of this study was to measure the net atmospheric exchange of CO<sub>2</sub> and CH<sub>4</sub> with  
73                   common high Arctic freshwater ecosystems, and place these findings in context with recent studies of terrestrial  
74                   GHG exchange from this remote polar semidesert biome.

## 75           **2 Methods**

### 76           **2.1 Location and sampling overview**

77                   We conducted our research at the Lake Hazen base camp in central Quttinirpaaq National Park, Ellesmere  
78                   Island, Nunavut (81.8° N, 71.4° W), Canada's most northerly protected area (Figure 1). Lake Hazen (area: 542 km<sup>2</sup>;  
79                   max. depth: 267 m) is the world's largest high Arctic lake, and is surrounded by a substantial watershed (6,901 km<sup>2</sup>).  
80                   About 42% of the Lake Hazen watershed is glaciated with the balance of area covered by a polar semidesert (>90%  
81                   of ice-free area; Edlund, 1994), small lakes, ponds and meadow wetlands. The lower Lake Hazen watershed is a  
82                   high Arctic thermal oasis (France, 1993) as it experiences anomalously warm growing season (June–August; 92



83 days) conditions because it is protected from cold coastal weather by the Grant Land Mountains and Hazen Plateau  
84 (Table S1). For example, mean July air temperature is typically 8-9 °C at the base camp, compared to July 1981-  
85 2010 climate normals of 6.1 °C and 3.4 °C at the coastal Eureka and Alert weather stations on Ellesmere Island,  
86 respectively (Environment Canada, 2016). Soils in the region are also atypically warm during the summer because  
87 of low moisture content and efficient radiative heating due to an abundance of clear-sky days. These conditions,  
88 coupled with continuous daylight during the growing season, have resulted in a greater diversity and abundance of  
89 vegetation and wildlife in the Lake Hazen watershed compared to surrounding areas (France, 1993), despite  
90 receiving only ~34 mm of precipitation during the growing season (Table S1). Ultra-oligotrophic Lake Hazen itself  
91 dominates the freshwater area of the watershed (Keatley et al., 2007) and receives most of its water annually from  
92 rivers discharging melt water from glaciers. Water exits Lake Hazen via the Ruggles River. Ice-cover can remain on  
93 Lake Hazen throughout the growing season, though in recent years the lake has gone ice-free more frequently,  
94 usually by late July. Ponds and a few small lakes are scattered throughout the lower watershed and are mostly  
95 shallow, small in area (~70% are <1 ha) and typically go ice-free by mid- to late-June each year.

96 To quantify net GHG exchange of typical high Arctic freshwater bodies, we identified several ponds or  
97 small lakes to sample within walking distance of base camp in the northwestern portion of the Lake Hazen  
98 watershed (Figure 1). These systems were chosen systematically to incorporate a gradient of watershed position,  
99 surface area, mean depth, emergent vegetation productivity, and hydrological connectivity (Table 1). We also  
100 sampled just offshore in Lake Hazen to obtain water representative of that which interacted with ponds located along  
101 its shoreline. All sampling occurred during the summer growing seasons of 2005 to 2012 (except for 2006), between  
102 mid-June and early August (Table S2).

## 103 **2.2 Dissolved CO<sub>2</sub> and CH<sub>4</sub> concentrations of high Arctic freshwaters**

104 Two approaches were used to quantify concentrations of dissolved CO<sub>2</sub> and CH<sub>4</sub> in surface waters. The  
105 first approach was employed at all sites and used the common method of collecting water directly into evacuated  
106 160-mL Wheaton glass serum bottles capped with butyl rubber stoppers (Hamilton et al., 1994; Kelly et al., 1997).  
107 Each bottle contained 8.9 g of potassium chloride (KCl) preservative to kill all microbial communities (Kelly et al.,  
108 2001), and 10 mL of ultra high purity dinitrogen (N<sub>2</sub>) as a gas headspace. To collect a sample, a bottle was  
109 submersed ~5 cm below the water surface and punctured with an 18-gauge needle. Barometric pressure and water  
110 temperature were recorded. Dissolved gas samples were stored in the dark at ~5 °C until return to the University of



111 Alberta, where they were analyzed in the accredited Biogeochemical Analytical Service Laboratory (BASL). There,  
112 samples were placed in a wrist-action shaker for 20 minutes to equilibrate dissolved CO<sub>2</sub> and CH<sub>4</sub> with the N<sub>2</sub>  
113 headspace. Headspace CO<sub>2</sub> and CH<sub>4</sub> concentrations were quantified on a Varian 3800 gas chromatograph (GC)  
114 using a flame ionization detector at 250°C with ultra high purity hydrogen (H<sub>2</sub>) as a carrier gas passing through a  
115 hayesep D column at 80°C. A ruthenium methanizer converted CO<sub>2</sub> to CH<sub>4</sub>. Four gas standards (Praxair, Linde-  
116 Union Carbide), ranging from 75 to 6000 ppm for both CO<sub>2</sub> and CH<sub>4</sub>, were used to calibrate the GC. A Varian Star  
117 Workstation program integrated peak areas and only calibration curves with an  $r^2 > 0.99$  were accepted for analyses.  
118 A standard was re-analyzed every 10 samples to reconfirm the calibration, and duplicate injections were performed  
119 on all samples. Headspace CO<sub>2</sub> and CH<sub>4</sub> concentrations were converted to dissolved molar concentrations using  
120 Henry's Law, and corrected for temperature and barometric pressure differences between sample collection and  
121 analysis. To quantify dissolved inorganic carbon (DIC) concentrations, samples were acidified with 0.5 mL H<sub>3</sub>PO<sub>4</sub>  
122 to convert all DIC to CO<sub>2</sub>, and then immediately reanalyzed on the GC. DIC concentrations were calculated as  
123 above.

124 The second approach involved two automated systems to determine detailed diel changes in surface water  
125 dissolved CO<sub>2</sub> concentrations at two different sites (Skeleton Lake and Pond 01; Figure 1; Table S2). Dissolved CO<sub>2</sub>  
126 concentrations were measured every three hours during several summers. These systems functioned by equilibrating,  
127 over a 20-minute period, dissolved CO<sub>2</sub> from pumped surface waters, with a gas cell in a Celgard MiniModule  
128 Liqui-Cel. The equilibrated gas was then analysed for CO<sub>2</sub> concentration by a LI-COR (Lincoln, NE) 820 infrared  
129 gas analyzer. The systems also measured dissolved oxygen (O<sub>2</sub>) concentrations using a Qubit<sup>TM</sup> flow-through  
130 sensor. Concentrations were then converted to aqueous molar concentrations using Henry's Law and water  
131 temperature quantified with a Campbell Scientific (Logan, UT) 107-L thermistor. The systems were housed in  
132 watertight cases along the shore from which a sample line extended out into the surface waters, and upon which was  
133 mounted a CS 014A anemometer (1 m height) and a Kipp & Zonen (Delft, The Netherlands) photosynthetically-  
134 active radiation (PAR) LITE quantum sensor. All data were recorded on Campbell Scientific CR10X dataloggers.

135 **2.3 Dissolved CO<sub>2</sub> and CH<sub>4</sub> concentrations of high Arctic freshwaters**

136 Though several models exist for quantifying turbulent gas fluxes of lakes (e.g., MacIntyre et al., 2010), we  
137 decided to use the stagnant film model described by Liss and Slater (1974) to quantify net CO<sub>2</sub> and CH<sub>4</sub> mass fluxes  
138 between surface waters and the atmosphere at our remote location. This decision was made because 24-hour



139 daylight at our high-latitude location damped diurnal surface temperature changes to less than 1°C, the general  
140 shallowness of the systems, and the steady, sometimes gusty, wind conditions on site. The stagnant film model  
141 assumes gas concentrations in both surface waters and the atmosphere are well-mixed, and that gas transfer between  
142 the phases occurs via diffusion across a diminutive stagnant boundary layer. Diffusive gas transfer across the  
143 boundary layer is assumed to follow Fick's First Law:

$$144 \quad \text{Gas flux } (\mu\text{mol m}^{-2} \text{ hr}^{-1}) = k(C_{\text{SUR}} - C_{\text{EQL}}) \quad (1)$$

145 where  $C_{\text{SUR}}$  ( $\mu\text{mol L}^{-1}$ ) is the concentration of the gas in surface waters,  $C_{\text{EQL}}$  ( $\mu\text{mol L}^{-1}$ ) is the atmospheric  
146 equilibrium concentration, and  $k$  is the gas exchange coefficient, or the depth of water per unit time in which the  
147 concentration of the gas equalizes with the atmosphere (i.e., piston velocity). Values of  $k$  ( $\text{cm hr}^{-1}$ ) were calculated  
148 using automated systems wind measurements and occasionally from nearby (within 2 km) eddy covariance towers  
149 (Campbell Scientific CSAT3 Sonic Anemometers; 30 min. means), and published empirical relationships (Table S3;  
150 Hamilton et al., 1994). To determine the direction of the flux, atmospheric equilibrium  $\text{CO}_2$  and  $\text{CH}_4$  concentrations  
151 were quantified using Henry's law, in-situ barometric pressure and air temperature, and mean annual  $\text{CO}_2$  and  $\text{CH}_4$   
152 concentrations in the atmosphere during the year of sampling (Environment Canada, 2015). If dissolved  $\text{CO}_2$  and  
153  $\text{CH}_4$  concentrations in surface waters were above or below their corresponding calculated atmospheric equilibrium  
154 concentrations, the freshwater systems were considered a source (+) or sink (-) relative to the atmosphere,  
155 respectively.

156 We also measured ebullition fluxes of  $\text{CH}_4$  to the atmosphere from two freshwater systems (Skeleton Lake,  
157 Pond 01) during two growing seasons using manual bubble collection and GC analysis (see Supporting  
158 Information).

#### 159 **2.4 Supporting measurements**

160 We quantified additional physical and chemical parameters in surface waters at the same sites as we  
161 collected our GHG samples, although at reduced sampling frequencies (Table S2). At each site, temperature, pH,  
162 specific conductivity and dissolved  $\text{O}_2$  were measured in-situ using a YSI (Yellow Springs, OH) 556 MPS multi-  
163 probe. Water samples were also collected for general chemical analyses (total dissolved nitrogen [TDN], particulate  
164 N,  $\text{NO}_3^- + \text{NO}_2^-$ ,  $\text{NH}_4^+$ , total phosphorus [P], total dissolved P [TDP], alkalinity, dissolved organic carbon [DOC],  
165 total dissolved solids, major cations/anions, chlorophyll-a [chl-a]) into pre-cleaned HDPE bottles. These samples



166 were immediately processed in the Lake Hazen/Quttinirpaaq Field Laboratory clean room after water collection, and  
167 stored in the dark at ~5°C or frozen until analysed at the BASL.

168 **2.5 Net atmospheric exchange of CO<sub>2</sub> and CH<sub>4</sub> of a large high Arctic watershed**

169 To better understand the role of freshwater ecosystems in regional fluxes of carbon GHGs, freshwater CO<sub>2</sub>  
170 and CH<sub>4</sub> fluxes measured in this study were coupled with terrestrial fluxes measured in the watershed during the  
171 2008-12 growing seasons (Emmerton et al., 2014; Emmerton et al., 2016). Areal coverage of the different ecosystem  
172 types in the watershed was isolated from a previous classification of Quttinirpaaq National Park (Edlund, 1994)  
173 using a Geographical Information System (ArcGIS v.10.3; ESRI, Redlands, US). Mean growing season fluxes from  
174 each measured ecosystem were then weighted to matching coverage area in the watershed to estimate the total  
175 carbon gas exchange with the atmosphere. Glacial ice was assumed to be a net-zero contributor of total watershed  
176 gas exchange in this scaling exercise.

177 **3 Results**

178 **3.1 Biogeochemical classification of high Arctic ponds**

179 Four distinct types of freshwater systems were evident from our sampling in the Lake Hazen watershed  
180 (Table 2; Figure 2; hierarchical cluster analysis; see Supporting Information). “Evaporative” ponds (Ponds 07, 10,  
181 12) occurred in the upland of the Lake Hazen catchment and were hydrologically-isolated from their surrounding  
182 basins post-snowmelt. These ponds were relatively high in concentrations of total dissolved solids, most measured  
183 ions, DIC, DOC, organic particles, TDP and chl-a. Pond 03, though not technically clustered with others, was forced  
184 to the Evaporative pond category based on lack of consistent inflowing water and high concentrations of most  
185 dissolved ions. This delegation was further consistent with isotopic measurements of oxygen ( $\delta^{18}\text{O}-\text{H}_2\text{O}$ ) in water  
186 taken from each aquatic system in July 2010 (Figure S2). “Meltwater” systems, including Ponds 11, 16 and Skeleton  
187 Lake, also occurred in the upland of the Lake Hazen watershed, but received consistent water supply through the  
188 growing season primarily from snowmelt, permafrost thaw water and/or upstream lake drainage. The general  
189 chemistry of these systems was therefore consistent and without extremes during the growing season. Typical  
190 meltwater streams draining to these ponds were high in TDN and sulfate (SO<sub>4</sub><sup>2-</sup>; Table 2). “Shoreline” ponds (Ponds  
191 01, 02) occurred along the margin of Lake Hazen and were typically physically isolated from the large lake by  
192 porous gravel berms, and surrounded by wetland soils and flora during spring low water conditions. As glacial melt



193 accelerated throughout the growing season, though, the water level of Lake Hazen rose and could seep through the  
194 berms to incrementally flood the ponds and surrounding wetlands (Figure S3). Shoreline ponds changed chemically  
195 during the onset of flooding as indicated, for example, by an increase in the concentration of reduced ions (i.e.,  
196  $\text{NH}_4^+$ ; Table S4). A separate smaller cluster of Pond 01 samples occurred during particularly high-water periods  
197 when Lake Hazen breached the berms (Figure 2). The flooding water from the “Lake Hazen shoreline” was cold,  
198 dilute in dissolved ions, organic matter, TDN, and chl-a, but considerably higher in  $\text{NO}_3^-$  compared to other water  
199 bodies. A single sample from a pre-flooded Shoreline pond (Pond 02) grouped within the Lake Hazen shoreline  
200 cluster likely because its water was ultimately sourced from Lake Hazen and because of its isolation from its  
201 wetland margins during low-water conditions.

202 **3.2 Dissolved concentrations and net atmospheric exchange of  $\text{CO}_2$  and  $\text{CH}_4$  of high Arctic freshwaters**

203 **3.2.1  $\text{CO}_2$**

204 Growing season concentrations of dissolved  $\text{CO}_2$  in sampled high Arctic freshwaters from 2005 to 2012  
205 varied substantially within and between the system types, and therefore overall resulted in non-significant  
206 differences between them (Figure 3, 4; linear mixed-model;  $\alpha=0.05$ ; see Supporting Information).

207 On average, Evaporative ponds had the highest mean  $\text{CO}_2$  concentrations (mean $\pm$ SE;  $27.9\pm4.9 \mu\text{mol L}^{-1}$ )  
208 compared to other pond types, primarily due to conditions in Pond 03 and Pond 07. These ponds were the shallowest  
209 of the four sampled and were rich in reduced ions, DIC, DOC, total P and calcium.  $\text{CO}_2$  concentrations were above  
210 atmospheric equilibrium concentration and therefore these ponds were sources of the gas to the atmosphere  
211 ( $+177\pm66 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ ; Figure S4). The other Evaporative ponds (Ponds 10, 12) were deeper and had  $\text{CO}_2$   
212 concentrations that were typically near those of the atmosphere. This contributed to their near-zero exchange of  $\text{CO}_2$   
213 with the atmosphere ( $-5\pm17 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ ). When combining all Evaporative ponds together, they were net  
214 sources of  $\text{CO}_2$  to the atmosphere ( $+73\pm93 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ ).

215 Meltwater systems had lower, but insignificantly different,  $\text{CO}_2$  concentrations ( $26.2\pm3.9 \mu\text{mol L}^{-1}$ ) than  
216 Evaporative ponds. Meltwater systems showed only gradual, venting-related declines of  $\text{CO}_2$  concentrations through  
217 the summer, with strong consistency in concentrations between sampling times and sites. However, they emitted  
218 higher, though not significantly different, fluxes of  $\text{CO}_2$  to the atmosphere overall ( $+160\pm66 \mu\text{mol m}^{-2} \text{ hr}^{-1}$ ; Figure 4)  
219 compared to the other types of systems.  $\text{CO}_2$  concentrations of these systems correlated strongly and positively with  
220  $\text{CH}_4$  concentrations, but negatively with other measurements that were of high concentrations in meltwater streams



221 draining into the systems (e.g.,  $\text{SO}_4^{2-}$ , TDN; Table 2, S4). Mean diurnal trends in  $\text{CO}_2$  concentrations across all  
222 sampling years, as measured by the automated system at Skeleton Lake, showed that  $\text{CO}_2$  and  $\text{O}_2$  concentrations  
223 associated positively together, but negatively with water temperature (Figure 5).

224 Mean  $\text{CO}_2$  concentrations of Shoreline ponds ( $22.5 \pm 3.7 \text{ } \mu\text{mol L}^{-1}$ ) were similar to the other pond types,  
225 which obscured their considerable seasonal changes within and between growing seasons. From 2005 to 2007, both  
226 Pond 01 and Pond 02 received little floodwater from Lake Hazen due to lower lake water levels. These conditions  
227 resulted in dense wetland vegetation growth surrounding the ponds and low mean daily dissolved  $\text{CO}_2$   
228 concentrations ( $6.5 \pm 0.4 \text{ } \mu\text{mol L}^{-1}$ ) and strong uptake of atmospheric  $\text{CO}_2$  ( $-329 \pm 59 \text{ } \mu\text{mol m}^{-2} \text{ hr}^{-1}$ ). The drier wetland  
229 state of these ponds changed in following summers when Lake Hazen rose substantially upon greater inputs of  
230 glacial meltwaters (WSC, 2015), causing the rising waters to seep through porous berms into the ponds through  
231 July. In concert with flooding, concentrations of  $\text{CO}_2$  from 2008-11 of each pond together increased substantially  
232 ( $30.1 \pm 1.5 \text{ } \mu\text{mol L}^{-1}$ ) resulting in strong net emissions of  $\text{CO}_2$  to the atmosphere ( $+228 \pm 44 \text{ } \mu\text{mol m}^{-2} \text{ hr}^{-1}$ ).  $\text{CO}_2$   
233 concentrations of the ponds correlated strongly and positively with concentrations of many constituents in the same  
234 waters (Table S4). Diurnal trends of  $\text{CO}_2$  and  $\text{O}_2$  concentration measured by the automated system at Pond 01 over  
235 several growing seasons showed a primary production signature with opposite temporal patterns of the gases, with  
236 greater  $\text{O}_2$  during the warmest and lightest parts of the day (Figure 5). However, the net result of strong seasonality  
237 in these ponds was slight net emission of  $\text{CO}_2$  to the atmosphere ( $+42 \pm 60 \text{ } \mu\text{mol m}^{-2} \text{ hr}$ ) that was not statistically-  
238 different from other types of systems.

239 Lake Hazen shoreline water, though not necessarily representative of the entire lake itself, was  
240 characteristic of its moat occurring early each growing season, and of water that intruded Shoreline ponds in July.  
241 This water was generally near atmospheric equilibrium concentrations of  $\text{CO}_2$  ( $21.0 \pm 7.8 \text{ } \mu\text{mol L}^{-1}$ ) with stable and  
242 low  $\text{CO}_2$  uptake throughout the season ( $-44 \pm 66 \text{ } \mu\text{mol m}^{-2} \text{ hr}$ ).  $\text{CO}_2$  concentrations of this shoreline water related  
243 strongest and positively with DIC, major ions and wind speed (Table S4).

### 244 3.2.2 $\text{CH}_4$

245 Each of Evaporative, Meltwater and Lake Hazen shoreline freshwaters had statistically similar and low  
246  $\text{CH}_4$  concentrations ( $0.06$ - $0.14 \text{ } \mu\text{mol L}^{-1}$ ) and fluxes ( $0$ - $3 \text{ } \mu\text{mol m}^{-2} \text{ hr}^{-1}$ ) across all growing seasons (Figure 3,4, S4).  
247 Evaporative ponds had generally flat seasonal  $\text{CH}_4$  concentration and flux trends, except for an outlier sample from  
248 Pond 10 in mid July 2011. Meltwater systems were also generally low in  $\text{CH}_4$  concentrations and fluxes through the



249 summers and associated strongly with similar chemical measures as CO<sub>2</sub> (Table S4). Notable flux emissions from  
250 these systems only occurred during episodic wind events, also similar to CO<sub>2</sub> (Figure S4). However, unlike CO<sub>2</sub>,  
251 higher CH<sub>4</sub> concentrations were sustained into July in Skeleton Lake in 2010. Lake Hazen shoreline water showed  
252 low and stable CH<sub>4</sub> concentrations and fluxes each growing season with infrequent and small releases of the gas to  
253 the atmosphere. CH<sub>4</sub> concentrations in this water correlated positively and strongly with particulate carbon  
254 concentrations (Table S4).

255 Shoreline ponds, alternatively, had significantly higher CH<sub>4</sub> concentrations relative to the other systems  
256 (1.18±0.16 µmol L<sup>-1</sup>) and showed a dynamic seasonal pattern dominated by the timing of flooding. In 2005 and  
257 2007 before substantial seasonal flooding started to occur, CH<sub>4</sub> concentrations (0.29±0.03 µmol L<sup>-1</sup>) and fluxes to  
258 the atmosphere (8±2 µmol m<sup>-2</sup> hr<sup>-1</sup>) were low. As the Shoreline ponds began to receive NO<sub>3</sub><sup>-</sup>-rich flood water from  
259 Lake Hazen by mid-summer in subsequent years (Table S4), 2008-11 CH<sub>4</sub> concentrations and fluxes increased  
260 substantially (1.70±0.13 µmol L<sup>-1</sup>; 41±10 µmol m<sup>-2</sup> hr<sup>-1</sup>). This significant increase in CH<sub>4</sub> flux emissions from  
261 Shoreline ponds during flooding (>five times higher than during dry periods) was coupled with large increases in  
262 pond surface areas, effectively producing even higher total CH<sub>4</sub> emissions to the atmosphere. Towards the end of  
263 July during flooding conditions, full berm breach of the Shoreline ponds by rising Lake Hazen waters occurred  
264 resulting in rapid dilution of CH<sub>4</sub> concentrations, but logistical constraints prevented later summer sampling to  
265 investigate if concentrations rebounded thereafter. Overall, aided by poor solubility of CH<sub>4</sub> in water and episodic  
266 wind events (Figure S4), the flooding of Shoreline ponds drove significantly larger CH<sub>4</sub> emissions to the atmosphere  
267 compared to other pond types (+28±5 µmol m<sup>-2</sup> hr<sup>-1</sup>; Figure 4).

268 **3.3 Net atmospheric exchange of CO<sub>2</sub> and CH<sub>4</sub> of a large high Arctic watershed**

269 Emmerton et al. (2014; 2016) measured, using eddy covariance flux towers (CO<sub>2</sub>, CH<sub>4</sub>) and static chambers  
270 (CH<sub>4</sub>), growing season carbon GHG exchange with terrestrial polar semidesert and meadow wetland landscapes  
271 from 2008-12. They found that the dry and mostly barren polar semidesert was among the most unproductive  
272 terrestrial ecosystems on Earth, taking up only -0.004 g C-CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> during the growing season, similar to findings  
273 from other studies (Soegaard et al., 2000; Lloyd, 2001; Lund et al., 2012). When scaled to total watershed area  
274 including Lake Hazen (7,443 km<sup>2</sup>), polar semidesert landscapes were inconsequential to total CO<sub>2</sub> exchange (-1,253  
275 Mg C-CO<sub>2</sub>; 9% of total exchange) despite comprising a substantial proportion of the catchment (3,819 km<sup>2</sup>; 51%;  
276 Figure 6). All types of standing freshwaters sampled in the watershed from this study showed statistically-similar



277 CO<sub>2</sub> fluxes compared to the polar semidesert. When assuming its shoreline waters were representative of the entire  
278 lake area, the expansive Lake Hazen (542 km<sup>2</sup>; 7%) exchanged relatively little CO<sub>2</sub> with the atmosphere (-721 Mg  
279 C-CO<sub>2</sub>; 5%), as did smaller freshwater systems (145 km<sup>2</sup>; 2%) in the watershed (+600 Mg C-CO<sub>2</sub>; 4%). In clear  
280 contrast, during the growing season, moist and vegetated meadow wetland ecosystems were found to consume CO<sub>2</sub>  
281 at rates similar to wetlands in the southern Arctic (-0.96 g C-CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>). Consequently, meadow wetlands  
282 exchanged an estimated 82% (-11,368 Mg C-CO<sub>2</sub>) of total CO<sub>2</sub> with the atmosphere despite occupying only 2%  
283 (129 km<sup>2</sup>) of the area in the Lake Hazen watershed. Total CO<sub>2</sub> exchange of the watershed was -10,236 Mg C-CO<sub>2</sub> (-  
284 1.375 g C-CO<sub>2</sub> m<sup>-2</sup>) during the growing season.

285 The high Arctic polar semidesert has recently gained attention as a notable atmospheric sink of CH<sub>4</sub> (-0.001  
286 g C-CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>; Emmerton et al., 2014), which has since been observed in studies at other high Arctic locations  
287 (e.g., Jorgensen et al., 2015). These uptake fluxes coupled with its expansive coverage made the polar semidesert the  
288 key landscape controlling net CH<sub>4</sub> exchange throughout the Lake Hazen watershed (-412 Mg C-CH<sub>4</sub>; 94% of total  
289 exchange; Figure 6). Surprisingly, a productive meadow wetland in the watershed was a weaker emitter of CH<sub>4</sub> to  
290 the atmosphere (+0.001 g C-CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>) compared to other high Arctic wetlands (Emmerton et al., 2014), releasing  
291 only 10 Mg C-CH<sub>4</sub> (2%) to the atmosphere during the growing season. All upland freshwater systems (Evaporative  
292 + Meltwater) had low emissions of CH<sub>4</sub> to the atmosphere (11 Mg C-CH<sub>4</sub>; 2%), as did Lake Hazen itself (+6 Mg C-  
293 CH<sub>4</sub>; 1%). All measured ecosystems had statistically-similar CH<sub>4</sub> fluxes except for the strong CH<sub>4</sub>-producing  
294 Shoreline ponds (Figure 6). However, poor areal coverage of these dynamic systems in the watershed (0.6 km<sup>2</sup>;  
295 <1%) resulted in contributions of <<1% (+0.4 Mg C-CH<sub>4</sub>) of all CH<sub>4</sub> exchange in the Lake Hazen watershed (-385  
296 Mg C-CH<sub>4</sub>; -0.052 g C-CH<sub>4</sub> m<sup>-2</sup>).

297 **4 Discussion**

298 **4.1 Dissolved concentrations and net atmospheric exchange of CO<sub>2</sub> and CH<sub>4</sub> of high Arctic freshwaters**

299 **4.1.1 CO<sub>2</sub>**

300 Concentrations of CO<sub>2</sub> and other compounds were highest in small and shallow Evaporative ponds (Ponds  
301 03, 07) compared with those that were larger and deeper (Ponds 10, 12). Dissolved CO<sub>2</sub> was likely being produced  
302 effectively in all Evaporative ponds by considerable ecosystem metabolism and accumulation and dissociation of  
303 weathered carbonates and evaporates (Trettin, 1994; Marcé et al., 2015). However, CO<sub>2</sub> was likely more effectively



304 diluted in the larger ponds and therefore less susceptible to wind-related turbulence and gas exchange with the  
305 atmosphere. Meltwater systems showed steady biogeochemical conditions but similar CO<sub>2</sub> concentrations as other  
306 freshwater types, despite inclusion of early summer sampling at Skeleton Lake (2007, 2010). High CO<sub>2</sub>  
307 concentrations in Skeleton Lake during that time were typical of post-ice covered waters only beginning to re-  
308 equilibrate with the atmosphere (Kling et al., 1992; Karlsson et al., 2013). Greater exchange of CO<sub>2</sub> by Meltwater  
309 systems, however, was not primarily driven by early season venting or sustained exchanges compared to other  
310 ponds, but rather by higher frequency of episodic releases of CO<sub>2</sub> to the atmosphere (Figure S4). This may have  
311 been related to their greater mean depths, which promoted stratification in at least one of our sampled Meltwater  
312 systems (Skeleton Lake; Figure S5). Stratification would confine decomposition products (e.g., CO<sub>2</sub>, CH<sub>4</sub>) to near  
313 their sites of origin in bottom sediments and extensive benthic mat communities (Rautio et al., 2011), which would  
314 then be released most readily during and after wind mixing events. We observed evidence of this process via strong  
315 positive associations between CO<sub>2</sub> and CH<sub>4</sub> concentrations in surface waters (Table S4). Further, mean diurnal CO<sub>2</sub>  
316 and O<sub>2</sub> concentrations in surface waters trended similarly with temperature- or wind-related solubility changes,  
317 rather than oppositely if metabolic processes (i.e., primary productivity or decomposition of organic matter) were  
318 important drivers in surface waters. Shoreline ponds changed drastically in size and chemistry in response to  
319 seasonal flooding by Lake Hazen shoreline water. During pre-flooding conditions, CO<sub>2</sub> concentrations were low  
320 which could be attributed to DIC use by autotrophic plankton (pre- to post-flooding mean chl-a concentrations of 1.2  
321 to 0.4 µg L<sup>-1</sup>), but more likely by observed dense benthic and macrophytic communities along the margins of the  
322 ponds. When inundated by flood waters, CO<sub>2</sub> concentrations rose sharply which is typically observed in flooded  
323 wetlands (Kelly et al., 1997). This occurs because widespread inundation of plants and soils typically prompts rapid  
324 decomposition and propagation of reduced compounds (e.g., NH<sub>4</sub><sup>+</sup>; Table S4). Although diurnal CO<sub>2</sub> and O<sub>2</sub>  
325 concentrations suggest that primary productivity was consistently occurring in Shoreline pond surface waters, this  
326 pattern appeared overwhelmed by acute seasonal adjustments in CO<sub>2</sub> exchange driven by flooding.

327 CO<sub>2</sub> concentrations in Lake Hazen shoreline water were near atmospheric equilibrium and only weakly  
328 consumed atmospheric CO<sub>2</sub>. These results along the shoreline appear to be similar to other locations offshore  
329 (unpublished) and were reflective of most deep lakes with extremely low nutrient, organic matter and chl-a  
330 concentrations (0.20 µg L<sup>-1</sup>; Keatley et al., 2007; Babaluk et al., 2009). CO<sub>2</sub> gas exchange between the lake and the  
331 atmosphere correlated well with DIC, alkalinity and other ions, which suggests supply and dissociation of carbonate



332 material from the watershed, as well as wind mixing, were important factors contributing to Lake Hazen surface  
333 water CO<sub>2</sub> concentrations, rather than primary productivity or heterotrophic decomposition.

334 **4.1.2 CH<sub>4</sub>**

335 Evaporative and Meltwater systems were typically weak producers and emitters of CH<sub>4</sub>, which was  
336 possibly sustained by concurrently high SO<sub>4</sub><sup>2-</sup> concentrations in these systems (Table 2; Trettin, 1994). This may  
337 have given competitive advantage to SO<sub>4</sub><sup>2-</sup>-reducing bacterial communities in sediments, which typically  
338 outcompete methanogenic bacteria for hydrogen. This hypothesis was supported by the prevalence of H<sub>2</sub>S gas in  
339 collected sediment cores from Skeleton Lake (unpublished) and by the trivial fluxes of CH<sub>4</sub> in bubbles measured  
340 emerging from sediments (0.00-0.01 mg m<sup>-2</sup> d<sup>-1</sup>; Table S5; see Supporting Information). Low production and  
341 exchange of CH<sub>4</sub> in Lake Hazen, alternatively, was most likely associated with the lake's ultra-oligotrophic  
342 standing, well-oxygenated water, and little accumulation of littoral organic matter where anoxia could prevail and  
343 CH<sub>4</sub> be produced. Only during periods of strong wind mixing of surface waters, or when Shoreline ponds breached  
344 and released particulate organic matter, did CH<sub>4</sub> release from the shoreline of the lake to the atmosphere increase  
345 above near-zero values.

346 Shoreline ponds were regional "hot-spots" of CH<sub>4</sub> exchange, which was clearly driven by seasonal  
347 flooding, similar to that described for CO<sub>2</sub> exchange. Pre-flooding conditions in the ponds were characterized by dry  
348 and oxygenated wetland soils which were exposed to the atmosphere and not connected to the central pond where  
349 we sampled. Flooding induced saturation of organic soils surrounding the wetland and perhaps provided  
350 advantageous conditions for anaerobic metabolism, including methanogenesis. This may have been further  
351 supported by the flushing of the ponds with SO<sub>4</sub><sup>2-</sup>-poor Lake Hazen water, therefore favoring metabolism of  
352 methanogens over SO<sub>4</sub><sup>2-</sup>-reducers in the flooded soils.

353 **4.3 Net atmospheric exchange of CO<sub>2</sub> and CH<sub>4</sub> of a large high Arctic watershed**

354 Most studies of terrestrial and freshwater carbon GHG exchange in the broader Arctic do not occur  
355 concurrently at a specific location. Our multiple season program of measuring carbon GHG exchange of both  
356 freshwater and terrestrial ecosystems provided a unique opportunity to delineate the relative strengths of freshwater  
357 and terrestrial contributions to regional carbon cycling in a high Arctic watershed (Table 3). Polar semideserts are  
358 typically dry and barren landscapes with little vegetation growth or organic matter and nutrient accumulation to



359 drive atmospheric exchange of CO<sub>2</sub>. Not surprisingly, freshwaters receiving runoff from the polar semidesert also  
360 support mostly underproductive ecosystems which exchange little CO<sub>2</sub> with the atmosphere (Figure 6). Lake Hazen,  
361 similarly, is sustained by cold and sediment-laden glacial melt water limited in compounds essential for life.  
362 Together, these oligotrophic freshwater and terrestrial ecosystems largely characterize the current low-production  
363 state of the Lake Hazen watershed and much of the high Arctic in general. Meadow wetlands, alternatively, are  
364 topographical lowlands with flowing water which are ideal high Arctic environments for vegetation growth and  
365 accumulation of soils rich in organic matter and nutrients. Conditions in these spatially-limited meadow wetlands  
366 are so profound relative to other ecosystem types in the Lake Hazen watershed that they currently drive a strong  
367 majority of atmospheric CO<sub>2</sub> exchange there. Evidently, CO<sub>2</sub> uptake across this, and likely other, high Arctic  
368 landscapes is inherently tied to the availability and movement of water.

369        Though polar semidesert landscapes exchanged only limited amounts of CO<sub>2</sub> with the atmosphere, they  
370 were extremely important sinks of atmospheric CH<sub>4</sub>, such that they dominate high Arctic CH<sub>4</sub> cycling. This strong  
371 sink has been attributed to soil conditions that promote efficient atmospheric gas diffusion and temperature  
372 sensitivity of methanotrophic bacteria at high latitudes (Emmerton et al., 2014; Jorgensen et al., 2015). Any  
373 ecosystems where water saturation and anoxia would be expected to prevail during the growing season (i.e., small  
374 ponds, lakes and meadow wetlands) were surprisingly weak emitters of CH<sub>4</sub>. This may have been due to poor  
375 quantities of organic substrates in the soils or beds of these systems, oxidation zones near gas exchange sites, or  
376 biogeochemical constraints related to SO<sub>4</sub><sup>2-</sup>. Regardless, CH<sub>4</sub> exchange in high Arctic ecosystems, at least those  
377 similar to the landscape composition of the Lake Hazen watershed, cannot be overlooked as substantial sinks of this  
378 potent GHG. However, these conditions, which currently define carbon GHG exchange in the Lake Hazen  
379 watershed, may be poised to change.

380        Warming growing season conditions in the Lake Hazen watershed have affected temperature sensitive  
381 components of the landscape including deep soils and permafrost (unpublished). Warming has also affected the  
382 region's hydrology through the greater delivery of glacial melt water to Lake Hazen and increased frequency and  
383 extent of ice-free area across the lake. Further, other studies suggest that changing air masses and evaporation from  
384 newly exposed coastal waters due to sea ice loss will deliver increased precipitation to high Arctic landscapes  
385 (Bintanja and Selten, 2014). These intensifying temperature and precipitation conditions will likely accelerate  
386 landscape changes in the watershed, especially considering the contemporary climate in the region is one at the low



387 global extreme of summer air temperatures and water availability. For example, Evaporative ponds could expand  
388 and deepen with greater precipitation and snow runoff, possibly repressing CO<sub>2</sub> emissions similar to Ponds 10 and  
389 12. Greater heating without sustained precipitation may alternatively cause these systems to continue to shallow and  
390 possibly strengthen GHG emissions to the atmosphere, similar to Ponds 03 and 07, but would be susceptible to  
391 ultimate drying (Smol & Douglas, 2007). Meltwater systems, alternatively, may be resistant to climate-related  
392 influences because of their already steady water supply and greater volumes, though future water delivery may be  
393 affected by diminishing stores of permafrost ice in soils. Shoreline ponds ultimately may endure the most substantial  
394 changes in GHG emissions of high Arctic water bodies. Lake Hazen, under warming and wetting conditions, would  
395 be expected to receive greater amounts of glacial melt water runoff during the growing seasons. Earlier rises in Lake  
396 Hazen water levels would cause earlier flooding of Shoreline ponds and sustain longer periods of organic soil and  
397 vegetation inundation, resulting in larger CO<sub>2</sub> and CH<sub>4</sub> emissions to the atmosphere. Eventually, though, extensive  
398 flooding may prevent the macrophyte growth currently found in these Shoreline ponds, decreasing the amount of  
399 fresh organic available for decomposition once the flooding occurs. However, based on areal coverage in the  
400 watershed, future changes in the GHG exchange of the region is likely dependent on changes occurring at the polar  
401 semidesert and in Lake Hazen itself. Polar semideserts and meadow wetlands represent a gradient of productivity  
402 defined by increasing water availability. If increased heating and precipitation results in greater soil retention of  
403 water and support for greater summer vegetation, then the sink strength of CO<sub>2</sub> in the high Arctic may improve  
404 drastically, but may at the same time reduce atmospheric CH<sub>4</sub> oxidation in soils. However topographical constraints  
405 of water flow may limit the magnitude of vegetation growth in meadow wetlands and across the polar semidesert in  
406 the shorter term. For Lake Hazen itself, we may expect that a warming climate will hasten loss of ice from the lake,  
407 resulting in greater water column heating, longer growing seasons, and increased river inflow to the lake. This may  
408 induce more intense mixing and nutrient availability in the water column and perhaps higher productivity and CO<sub>2</sub>  
409 sequestration. Loss of glacial ice also presents new, but uncertain, opportunities of gas exchange on newly exposed  
410 landscapes.

411 Ultimately, freshwater systems in the Lake Hazen watershed did not produce considerable enough fluxes of  
412 GHGs relative to the atmosphere to dominate regional GHG exchange, as observed in other studies to the south.  
413 However, potential does exist in the watershed for hot-spots of GHG exchange to emerge from greater water  
414 availability, which is a distinct possibility in the near-future with ongoing rapid climate warming in the region.



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595 **Tables**

596 **Table 1 Morphometry and hydrology of ponds and lakes sampled for greenhouse gases concentrations and general  
 597 chemistry in the Lake Hazen (LH) watershed during the growing seasons of 2005, and 2007-2012.**

Lake or Pond (location)	Surface area (ha)	Mean depth (m)	Max. depth (m)	Elevation (m asl)	Primary water sources
Pond 01 (N81.822 W71.352)	0.2-0.7	0.2-0.6	0.5-1.3	166	LH, snowmelt
Pond 02 (N81.811 W71.453)	0.2-3.4	0.1-0.4	0.3-1.2	165	LH, snowmelt
Pond 03 (N81.829 W71.462)	0.04	0.3	0.8	338	Snowmelt
Pond 07 (N81.835 W71.305)	0.4	0.1	0.3	184	Snowmelt
Pond 10 (N81.838 W71.343)	2.5	1.1	2.4	222	Snowmelt
Pond 11 (N81.832 W71.466)	0.2	1.1	2.5	291	Snowmelt, permafrost
Pond 12 (N81.831 W71.529)	0.2	0.8	1.9	370	Snowmelt
Pond 16 (N81.850 W71.392)	0.8	1.1	2.1	434	Snowmelt, permafrost
Skeleton L. (N81.829 W71.480)	1.9	1.9	4.7	299	Snowmelt, permafrost
LH-shore (N81.821 W71.352)	54,200	95 <sup>a</sup>	267 <sup>a</sup>	158	Glacial, snowmelt

598 <sup>a</sup>Kock et al., 2012

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601 **Table 2 Mean water temperature and general chemistry of different freshwater types in the Lake Hazen (LH) watershed  
 602 during the growing seasons of 2005, 2007-2012. All measurements are in  $\mu\text{mol L}^{-1}$  except for  $W_T$  ( $^{\circ}\text{C}$ ), TDS (mg  $\text{L}^{-1}$ ) and  
 603 chl-a ( $\mu\text{g L}^{-1}$ ).**

Lake Type	$W_T$	pH	TDS	PC	DIC	DOC	$\text{NO}_3^-$	$\text{NH}_4^+$	TDP	Fe	$\text{SO}_4^{2-}$	Chl-a
Evaporative	10.8	8.3	1,020	49	2,122	2,374	0.01	0.5	0.32	1.13	5,320	1.3
Meltwater	11.0	8.2	333	23	1,458	452	0.02	1.9	0.17	0.05	1,755	0.5
Shoreline	11.6	8.2	173	32	1,691	311	0.11	2.0	0.18	1.56	365	0.4
LH-shoreline	5.4	7.9	59	10	524	51	0.24	1.8	0.08	0.04	69	0.1

604 Meltwater source 2.6 7.6 653 - 769 67 7.70 0.1 0.05 0.6 3318 -

605

606  $W_T$ : water temperature; TDS: total dissolved solids; PC: particulate carbon; DIC: dissolved inorganic carbon; DOC: dissolved  
 607 organic carbon;  $\text{NO}_3^-$ : dissolved nitrate + nitrite;  $\text{NH}_4^+$ : dissolved ammonium; TDP: total dissolved phosphorus; Fe: dissolved  
 iron;  $\text{SO}_4^{2-}$ : dissolved sulfate; chl-a: chlorophyll-a



608      **Table 3** Ranges or means of  $\text{CO}_2$  and  $\text{CH}_4$  fluxes ( $\text{g C m}^{-2} \text{ d}^{-1}$ ) from selected studies investigating terrestrial and  
 609      freshwater greenhouse gases exchange during the growing season of high, low and subarctic regions. Positive values  
 610      represent emission to the atmosphere.

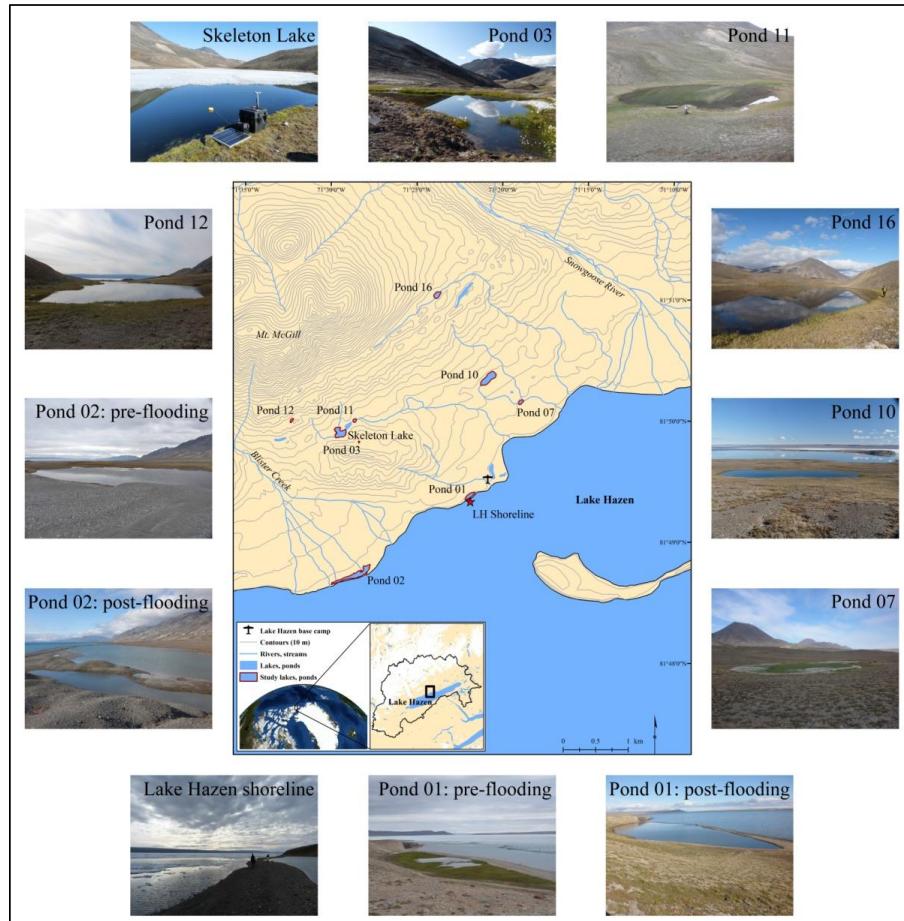
Location*	Ecosystem	Period	$\text{CO}_2$ flux	$\text{CH}_4$ flux	Study
<b>High Arctic</b>					
Lake Hazen, CA	Dry tundra	Jun.-Aug.	-0.00	-0.00	a, b
Zackenberg, GR	Heath	May-Sep.	-0.39,0.03	0.04,0.06	c, d
Lake Hazen, CA	Ponds	Jun.-Aug.	-0.01,0.05	0.00,0.01	This study
Pond Inlet, CA	Ponds	Jul.	-0.22,0.72	0.00,0.07	e
<b>Low Arctic</b>					
Lena delta, RU	Wet tundra	May-Aug.	-0.35	0.01	f, g
Barrow, US	Moist tundra	Jun.-Sep.	-0.02,0.66	0.02	h, i
Lena delta, RU	Ponds	Aug.-Sep.	0.38,1.10		j
Toolik Lake, US	Lakes	Jul.-Aug.	-0.07,0.72	0.96,12.25	k
Yukon delta, US	Lakes	Jun.-Aug.		0.04	l
<b>Subarctic</b>					
Chokurdakh, RU	Tundra	Jul-Aug		0.05	m
Abisko, SE	Shrub tundra	Jul-Aug.	-0.95,-0.83		n
Cherskii, RU	Tussock tundra	Jul.-Aug.	-0.15,0.50	0.32	o
James Bay, CA	Mixed tundra	Jun-Oct.		0.04	p
Narvik, SE	Lakes	May-Oct.	-0.03,0.13	0.00,0.02	q
Inuvik, CA	Lakes	Jun.-Aug.	-1.55,-0.65	-	r
Cherskii, RU	Ponds	Jun.-Sep.		0.09	s

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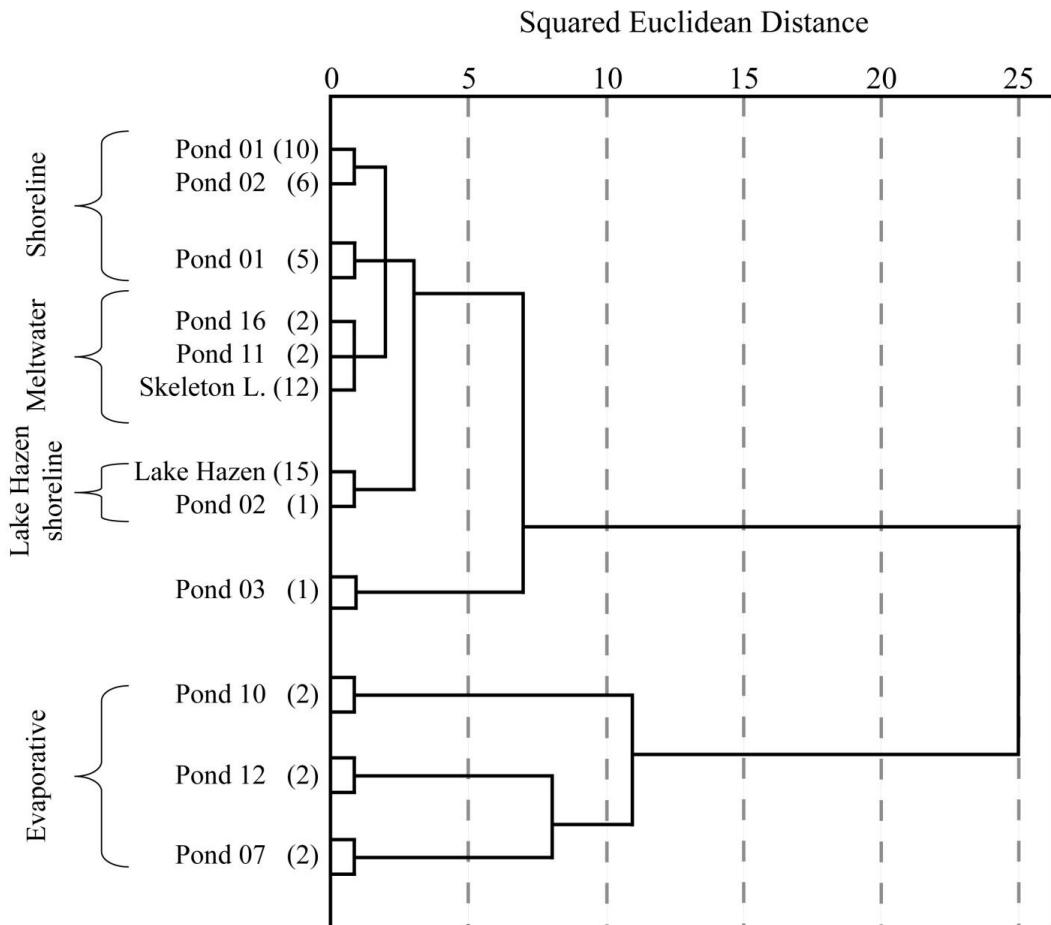
612      a Emmerton *et al.*, 2016; b Emmerton *et al.*, 2014; c Lloyd, 2001; d Tagesson *et al.*, 2012; e Laurion *et al.*, 2010; f Kutzbach *et*  
 613      *al.*, 2007; g Sachs *et al.*, 2010; h Kwon *et al.*, 2006; i Sturtevant and Oechel, 2013; j Abnizova *et al.*, 2012; k Kling *et al.*, 1992; l  
 614      Fan *et al.*, 1992; m Parmentier *et al.*, 2011; n Fox *et al.*, 2008; o Merbold *et al.*, 2009; p Roulet *et al.*, 1994; q Karlsson *et al.*,  
 615      2013; r Tank *et al.*, 2009; s Walter *et al.*, 2006; \*as delineated by AMAP, 1998.

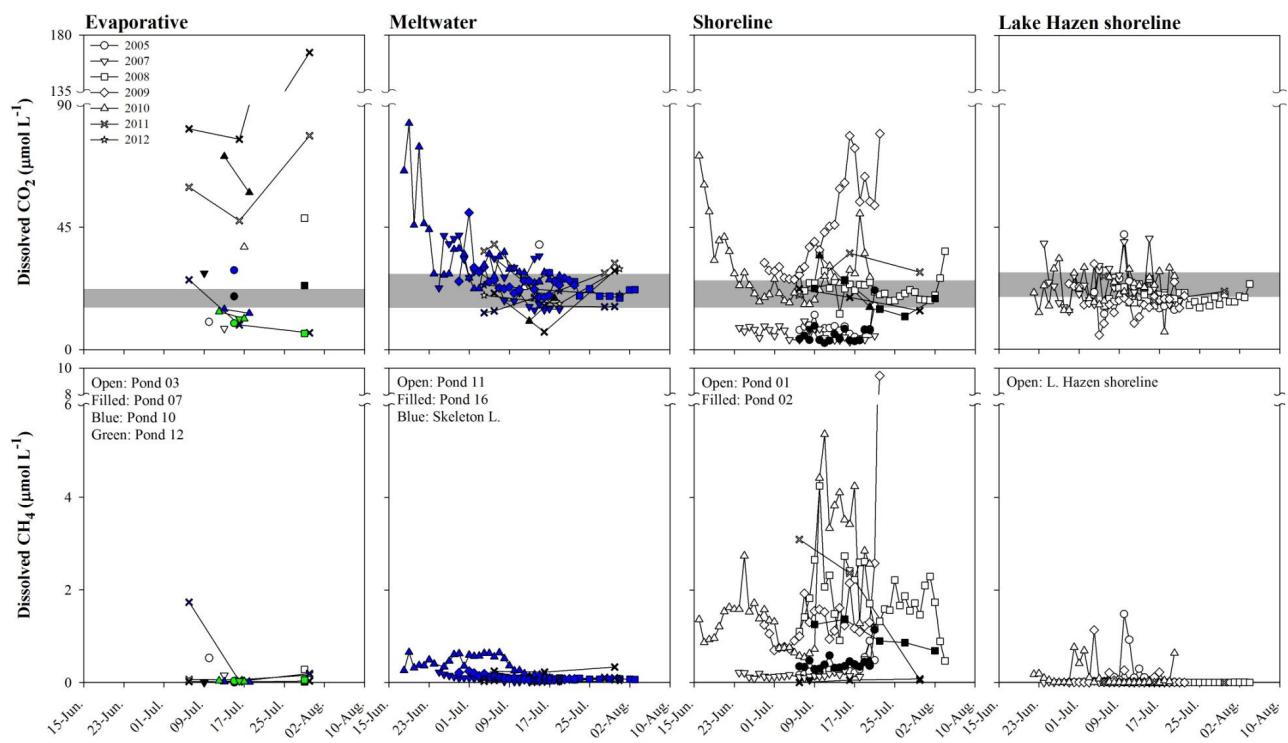


616 **Figures**



619 **Figure 1** Map of the Lake Hazen base camp in Quttinirpaaq National Park, Nunavut, Canada. Ponds and lakes  
620 investigated in this study are indicated on the map and shown in photographs. Shown inset of the map are the general  
621 locators of the Lake Hazen watershed.





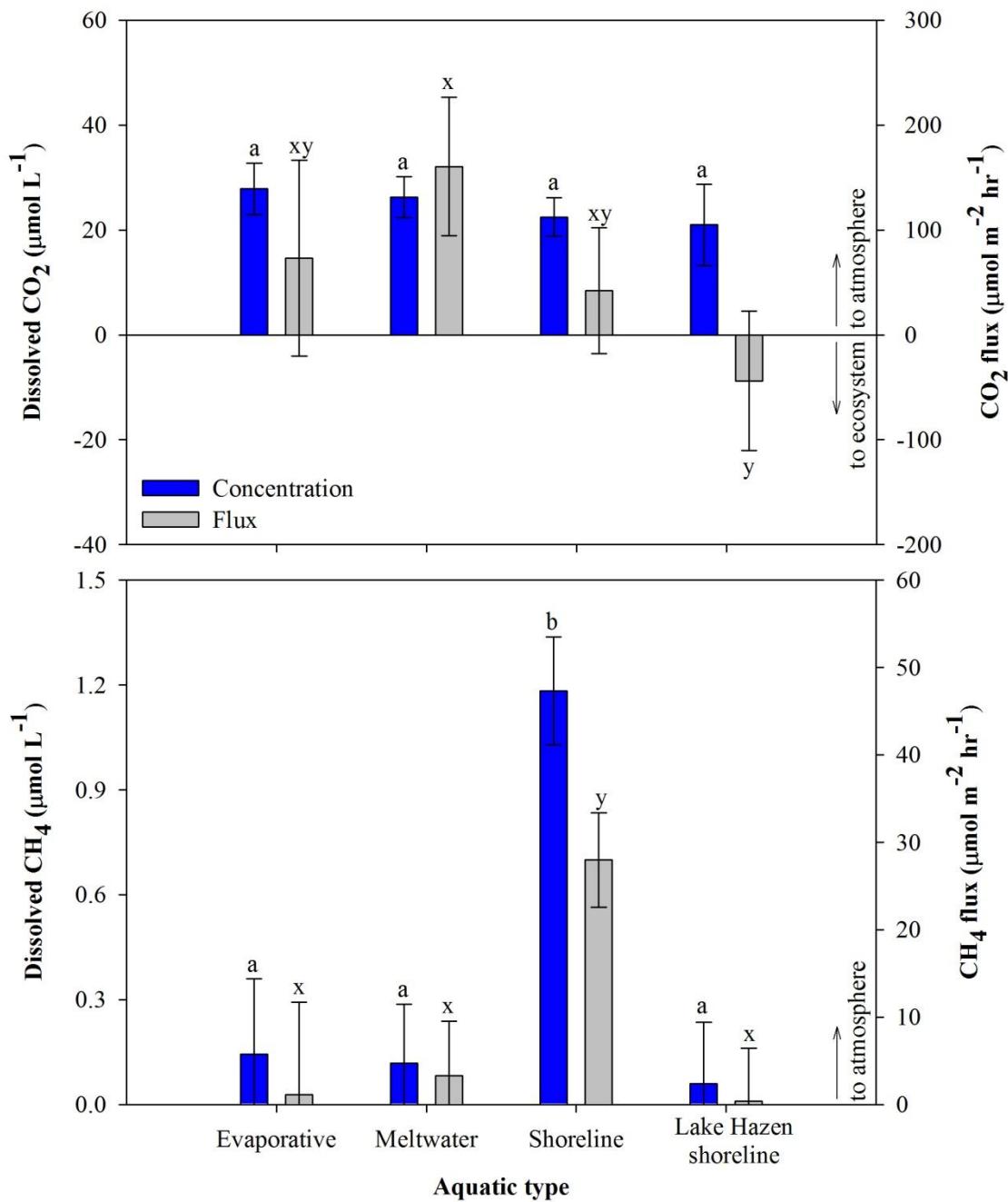
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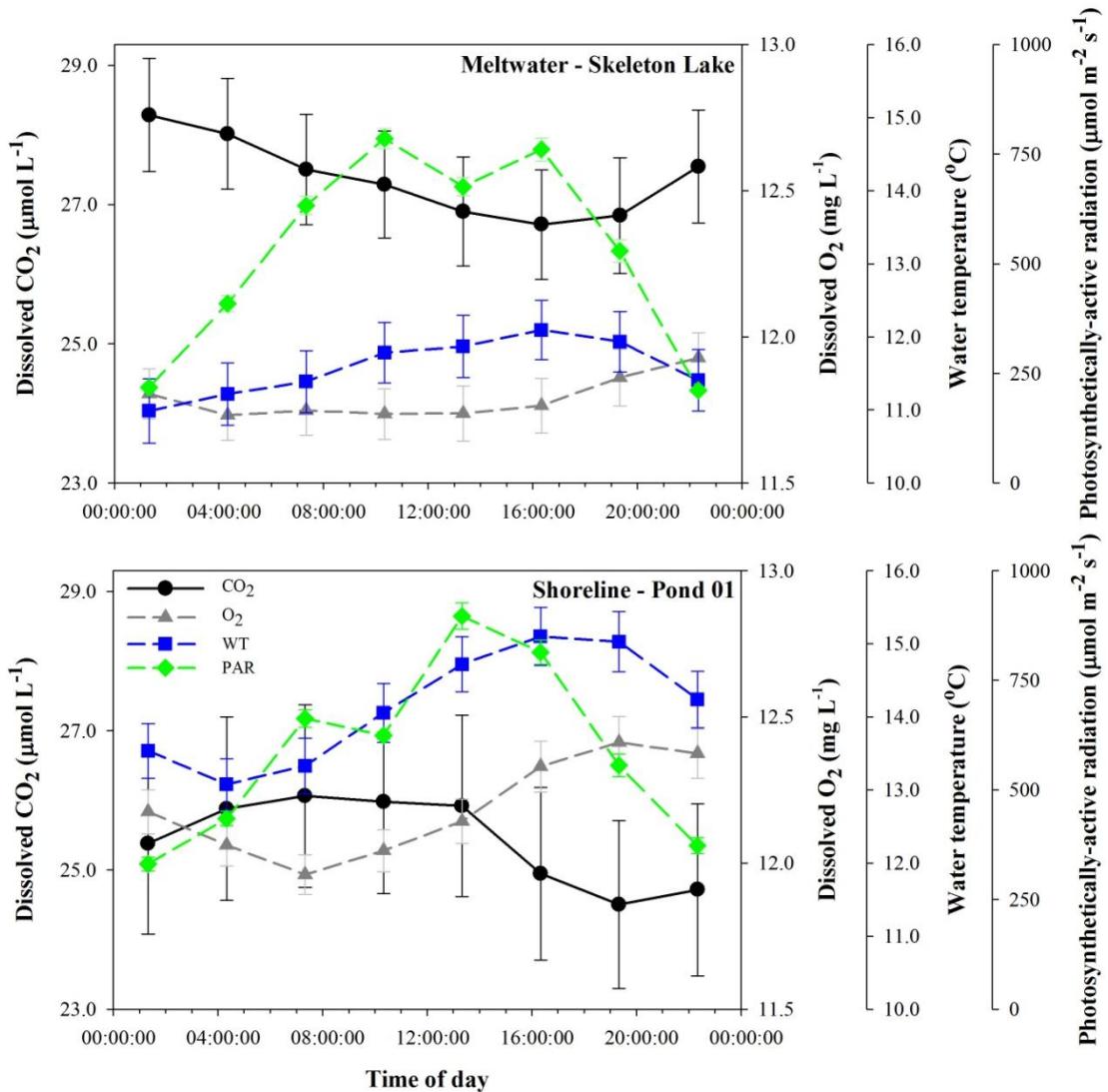
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Figure 3 Dissolved carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) concentrations during the 2005, and 2007-2012 growing seasons (June-August) from different types of high Arctic freshwater systems in the Lake Hazen watershed. Inset text shows site names within each freshwater type. Grey areas indicate the range of atmospheric equilibrium concentrations during the sampling period.



**Figure 4** Mean ( $\pm\text{SE}$ ) dissolved carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) concentrations and fluxes during the 2005, and 2007–2012 growing seasons from four different freshwater system types in the Lake Hazen watershed. Letters denote statistical differences between ecosystem types for each gas (linear mixed model;  $\alpha=0.05$ ; see Supporting Information).



**Figure 5** Three-hour diurnal dissolved carbon dioxide (CO<sub>2</sub>) concentration, oxygen (O<sub>2</sub>) concentration, water temperature and photosynthetically-active radiation (PAR) data measured by automated systems deployed at the shorelines of Skeleton Lake (2008–10) and Pond 01 (2008–10) during the high Arctic growing season in the Lake Hazen watershed.

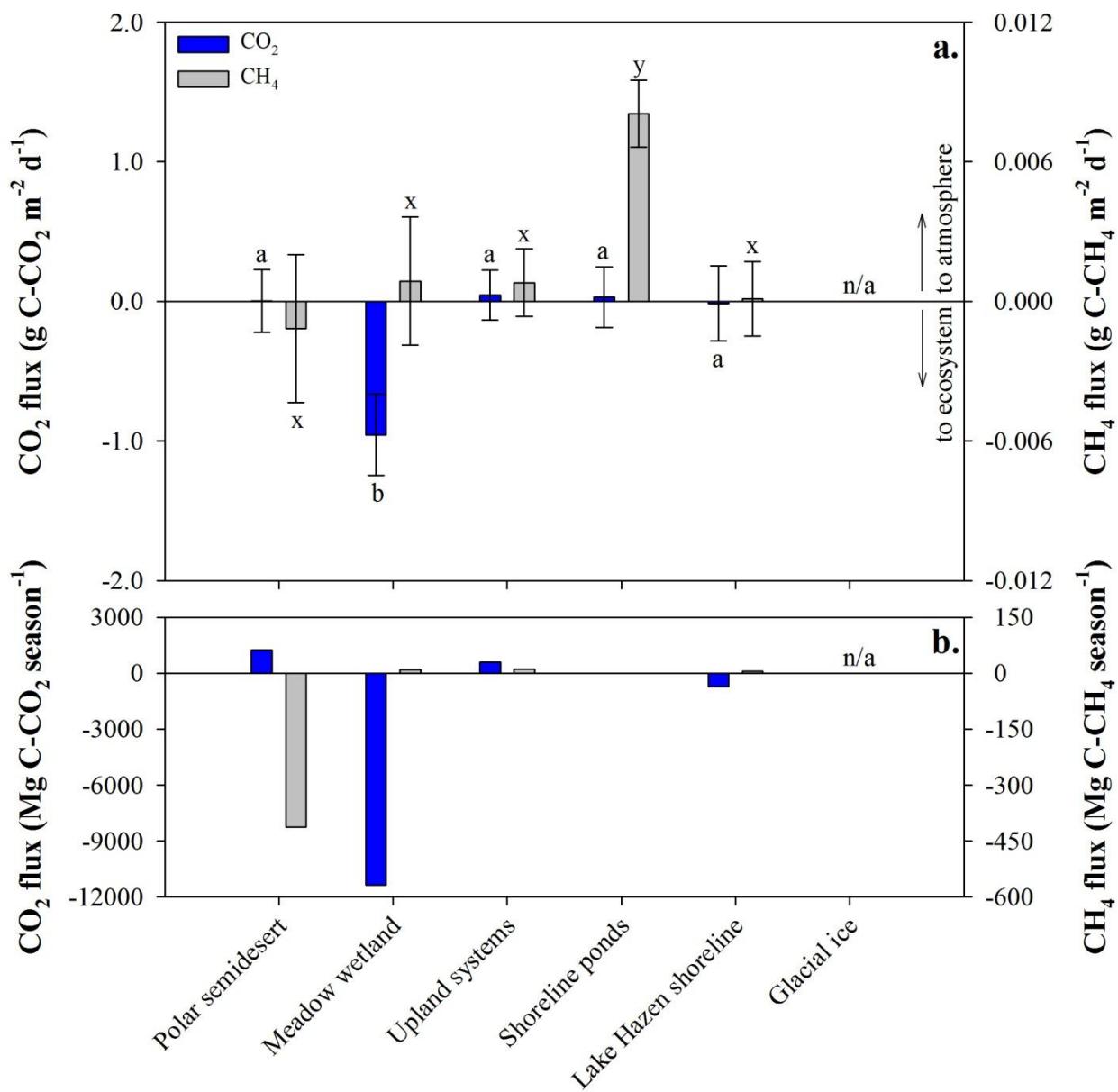


Figure 6 (a.) Comparison of the net exchange of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) between high Arctic terrestrial and freshwater ecosystems and the atmosphere in the Lake Hazen watershed during the growing seasons of 2005, and 2007-2012. Letters denote statistical differences between ecosystem types for each gas (linear mixed model;  $\alpha=0.05$ ; see Supporting Information). (b.) Total growing season (June-August) watershed exchange of CO<sub>2</sub> and CH<sub>4</sub> by terrestrial and freshwater types in the total Lake Hazen watershed.