

1 **The potential effects of fresh water content on the primary**
2 **production in the Chukchi Sea**

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17

18 **Abstract**

19 The *in situ* primary production rates and various environmental variables were investigated in the
20 Chukchi Sea during the 3rd-RUSALCA expedition, which was conducted in 2012, to identify the current
21 status of primary production. A ¹³C-¹⁵N dual tracer technique was used to measure the daily primary
22 production rates, which ranged from 0.02 to 1.61 g C m⁻² d⁻¹ (mean ± SD = 0.42 ± 0.52 g C m⁻² d⁻¹). The
23 primary production rates showed large regional differences, with the southern region (0.66 ± 0.62 g C m⁻²
24 d⁻¹) producing approximately five times as much as the northern region (0.14 ± 0.10 g C m⁻² d⁻¹), which
25 was primarily due to the differences in phytoplankton biomasses induced by regional nutrient conditions.
26 The primary production rates in the Chukchi Sea were averaged using data acquired during the three
27 different RUSALCA expeditions (2004, 2009, and 2012) as 0.33 g C m⁻² d⁻¹ (SD = 0.40 g C m⁻² d⁻¹),
28 which was significantly lower than previously reported rates. In addition to strong seasonal and
29 interannual variations in primary production, recent decreases in the concentrations of major inorganic
30 nutrients and chlorophyll *a* could be among the reasons for the recent low primary production in the
31 Chukchi Sea because the primary production is mainly affected by nutrient concentration and
32 phytoplankton biomass. The nutrient inventory and primary production appear to be largely influenced by
33 the freshwater content (FWC) variability in the region due to the significant relationships between FWC,
34 nitrate concentrations ($r = 0.54, p < 0.05$) and primary production rates ($r = 0.56, p < 0.05$). Moreover, we
35 found highly significant relationships between the nutrient levels and the primary production rates ($r =$

36 0.75, $p < 0.001$). In conclusion, the primary production in the Chukchi Sea is primarily controlled by
37 nutrient availability which is strongly related to the FWC variability. Our results imply that the predicted
38 increase in freshwater accumulation might cause a decrease in primary production by lowering the
39 nutrient inventory in the euphotic zone of the Chukchi Sea.

40

41 ***Keywords:***

42 Phytoplankton, Primary production, Chukchi Sea, Freshwater content, Arctic

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45 **1. Introduction**

46 Over recent years, the Arctic Ocean has undergone drastic changes in the extent and thickness of sea
47 ice (Stroeve et al., 2008; Comiso et al., 2008; Kwok et al., 2009; Overland and Wang, 2013). The
48 continuing loss of sea ice may result in changes to various physical and chemical environmental
49 conditions in the Arctic Ocean. For example, the loss in sea ice cover allows more sunlight to enter the
50 surface layer of the Arctic Ocean, which results in a longer growing season for phytoplankton growth
51 (Arrigo et al., 2008; Ardyna et al., 2014). Stroeve et al. (2014) reported that the arctic melt season has
52 lengthened at a rate of 5 days decade⁻¹ from 1979 to 2013, due to later autumn freeze-up. In accordance
53 with their findings, Ardyna et al. (2014) ~~revealed~~documented the development of a second bloom in the
54 Arctic Ocean during the fall, which coincides with the delayed freeze-up and the increased exposure to
55 wind stress.

56 However, the loss in sea ice can cause an increase in the input of freshwater (McPhee et al., 2009). In
57 fact, the freshwater volumes in the Canada and Makarov Basins increased by of 8500 km³ in 2008 due to
58 increased sea ice melting and river discharge (McPhee et al., 2009; Rabe et al., 2011). This phenomenon
59 can enhance the stratification in the upper ocean (Yamamoto-Kawai et al., 2009) and consequently reduce
60 vertical mixing, thereby preventing nutrient inputs from deep waters to the euphotic zone. In fact,
61 McLaughlin and Carmack (2010) found a deepening of the nutricline due to the accumulation of surface
62 freshwater in the Canada Basin.

63 In the Chukchi Sea as inflow shelf, there was an increased volume flux of 50% in 2011 (~ 1.1Sv)
64 relative to 2001 (~ 0.7 Sv), which was accompanied by increases in heat and freshwater fluxes (Woodgate
65 et al., 2012). Though the volume flux may vary both seasonally and annually under the influence of the
66 local wind fields, the recent increases in freshwater fluxes in the region may have important implications
67 for phytoplankton in terms of nutrient availability for their growth (Woodgate et al., 2005a, 2005b, 2006).
68 Thus, it is important to identify how phytoplankton respond to these environmental changes in the region
69 in terms of production and/or community structure. According to Li et al. (2009), the phytoplankton
70 community has changed under the freshening and stratifying condition in the Canada Basin. Notably, the
71 abundance of small phytoplankton (< 2 μm) has increased, whereas the abundance of large phytoplankton
72 (2-20 μm) has decreased. Yun et al. (2014) also found that compared with previous reports, the small
73 phytoplankton were more abundant on the Chukchi Sea shelf, which is dominated by low nutrients and
74 freshening conditions. Therefore, the changes in recent phytoplankton production under the rapidly
75 changing environmental conditions need to be monitored because the changes in phytoplankton
76 production could have important implications for understanding ecosystem changes in the Arctic Ocean.

77 In order to understand climate and ecosystem change in the Pacific Arctic Ocean which is a region
78 summer sea ice cover was declining dramatically (Crane and Ostrovskiy, 2015). The RUSALCA
79 (Russian-American Long-term Census of the Arctic) expedition, which is a joint US-Russian research
80 program, started from 2004 as multidisciplinary investigations in the Bering and Chukchi Seas. -Three

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81 RUSALCA expeditions (2004, 2009, and 2012) provided a good opportunity for continuous
82 measurements of the primary production in the entire Chukchi Sea, including the territorial waters of the
83 Russian Federation. The 1st-2004 RUSALCA expedition was conducted from 8 to 24 August, 2004 (Lee
84 et al., 2007). The 2nd-2009 RUSALCA expedition was executed from 1 to ~~31~~30 September, 2009 (Yun et
85 al., 2014). The 3rd-2012 RUSALCA expedition was carried out from 27 August to 16 September, 2012.
86 This study is part of the 3rd-2012 RUSALCA expedition.

87 In this study, we addressed the regional characteristics of primary production by examining the main
88 driving factors responsible for the regional variability in the Chukchi Sea based on measurements taken in
89 2012. In addition, we investigated the recent trends in primary production in the Chukchi Sea based on
90 the results of the three RUSALCA expeditions (2004, 2009, and 2012) in the Chukchi Sea. Finally, we
91 emphasized the potential effects of freshwater accumulation on the primary production in the Chukchi
92 Sea because changing amounts and distributions of freshwater content could lead to changes in the
93 primary production rates.

94

95 **2. Materials and methods**

96 *2.1. Study area and sampling*

97 The 3rd-RUSALCA expedition in 2012 was conducted onboard the Russian vessel *Professor Khromov*
98 in the Chukchi Sea from 27 August to 16 September, ~~2012~~. The study area was comprised of several

99 sections between the Bering Strait and the vicinity of Herald Canyon (Fig. 1). To understand the regional
100 characteristics of primary production, the study area was divided into two geographic regions
101 (northern/southern) following Yun et al. (2014). The northern region consisted of stations in the vicinity
102 of Herald Canyon (CEN and HC sections) (Fig. 1). The stations in the Chukchi South and Cape Lisburne
103 (CS and CL sections) were included in the southern region. Most of the bathymetric depths in the entire
104 study area were quite shallow, with a mean of 55 m (SD = ± 11 m). Between the production stations, the
105 depth of euphotic zone from the surface to 1% light depth varied between 20 and 46 m, with a mean of 29
106 ± 10 m (Table 1).

107 Oceanographic/biological samples were taken from a total of 54 conductivity-temperature-depth
108 (CTD) stations. The vertical profiles of water temperature and salinity were obtained using a Sea-Bird
109 model SBE911*plus* CTD profiler. Water samples were collected with a stainless-steel rosette sampler that
110 was equipped with 21 10-liter bottles at every CTD station. The data from the previous RUSALCA
111 expeditions (in 2004 and 2009) were included to understand the recent trends in primary production in the
112 Chukchi Sea.

113

114 2.2. *Physical and chemical variables*

115 The stratification index of the water column ($\Delta\sigma_t$) (in kg m^{-3}) was determined as the difference in $\Delta\sigma_t$
116 values between the surface and the bottom depth according to Yun et al. (2014). The surface mixed layer

117 (Z_m) was defined as the depth at which the density (σ_t) gradient was 0.05 kg m^{-3} higher than the
118 surface density, as in Coupel et al. (2015). The depth of the euphotic zone (Z_{eu}) in this study was defined
119 as the depth receiving 1% of the surface PAR value, as in Lee et al. (2007) and Yun et al. (2014), and was
120 obtained from a Biospherical QSP-2300 PAR sensor (Biospherical Instruments Inc.) that was lowered
121 with the CTD/rosette sampler. The nitracline (Z_{nit}) was determined as the depth at which the nitrate
122 gradient was greater than $0.1 \mu\text{M m}^{-1}$ according to the definition of Coupel et al. (2015).

123

124 2.3. Fresh Water Content (FWC)

125 To assess the surface water freshening, the freshwater content (FWC) was calculated following
126 Carmack et al. (2008):

$$127 \quad FWC = \int_{z_{lim}}^0 (1 - S(z)/S_{ref}) dz$$

128

129 where S and S_{ref} are the *in situ* and reference salinities, respectively, and Z_{lim} is the depth where S equals

130 S_{ref} (34.8 on the practical salinity scale). We used a reference salinity of 34.8 following Aagaard and

131 Carmack (1989) to computing freshwater since it has been considered as the mean salinity for the Arctic

132 Ocean.

133

134 2.4. Nutrient concentration measurements

135 The discrete water samples used in measuring the nutrient concentrations were obtained from 5 to 9
136 different depths depending on the water depths. The dissolved inorganic nutrient concentrations
137 (nitrite+nitrate, ammonium, phosphate, and silicate) were analyzed onboard immediately after collection
138 using an automated nutrient analyzer (ALPKEM RFA model 300) following the method of Whitledge et
139 al. (1981).

140

141 *2.5. Chlorophyll a concentration measurements*

142 The water samples used for measuring the chlorophyll *a* concentration were obtained from 4 to 7
143 different depths at most stations. The water samples were filtered through Whatman GF/F filters (24 mm),
144 and the filters were then kept frozen until analysis in the laboratory. The filters were subsequently
145 extracted in a 3:2 mixture of 90% acetone and DMSO in a freezer for 24 h, followed by centrifugation
146 (Shoaf and Lium, 1976). The chlorophyll *a* concentrations were measured using a Turner Designs model
147 10-AU fluorometer, which was calibrated using commercially available preparations of purified
148 chlorophyll *a* (Turner Designs, USA). The methods and calculations used to determine the chlorophyll *a*
149 concentrations followed the procedure of Parsons et al. (1984).

150

151 *2.6. In situ primary production measurements*

152 The water samples used to measure primary production were collected at six photic depths (100, 50,

153 30, 12, 5, and 1% penetration of the surface irradiance, PAR). At 11 selected morning stations, the *in situ*
154 primary productions of phytoplankton were measured using a ^{13}C - ^{15}N dual tracer technique (Lee and
155 Whitledge, 2005; Lee et al., 2007). This method could be useful for distinguish the relative importance of
156 nitrate and ammonium as nitrogen sources for the cell and population (Dugdale and Goering, 1967). We
157 followed the same analytical procedure of Lee et al. (2007) and Yun et al. (2014) to the measure primary
158 production to consistently compare the primary production levels determined in the three studies. Briefly,
159 heavy isotope-enriched (98-99%) carbon ($\text{NaH}^{13}\text{CO}_3$), nitrate (K^{15}NO_3), and ammonium ($^{15}\text{NH}_4\text{Cl}$)
160 substrates were inoculated in polycarbonate bottles (1 L) and then incubated on deck in a large
161 polycarbonate incubator cooled with running surface seawater under natural light conditions. After
162 approximately 4 to 5 h of incubation, all samples were filtered using pre-combusted (450°C , 4 h) glass
163 fiber filters (Whatman GF/F; diameter = 25 mm). After HCl fume treatment, the samples were sent to the
164 Alaska Stable Isotope Laboratory of the University of Alaska, Fairbanks, USA. The abundances of ^{13}C
165 and ^{15}N and the total amounts of particulate organic carbon (POC) and nitrogen (PON) were determined
166 using a Thermo Finnigan Delta+XL mass spectrometer. Finally, the carbon and nitrogen production rates
167 were calculated based on Hama et al. (1983) and Dugdale and Goering (1967), respectively.

168

169 **3. Results**

170 *3.1. Physical conditions*

171 The surface temperature (T_{sur}) varied from -2 to 9 °C in the study area in 2012 (Fig. 2a). The higher
172 temperatures were found in the eastern side of the southern Chukchi Sea due to the strong influence of the
173 Alaskan Coastal Water (warmer and less saline). The freezing temperatures were observed in the vicinity
174 of the Herald Canyon and gradually decreased toward the northward. At the surface, the salinity varied
175 between 21 and 33 psu. The surface salinity (S_{sur}) was considerably lower in the southwestern side
176 compared with the northeastern side of the southern Chukchi Sea (Fig. 2b). The stratification index ($\Delta\sigma_t$)
177 in the study area ranged from 0.7 to 9.7 kg m⁻³, with a mean of 3.8 ± 2.2 kg m⁻³. The stratification in the
178 southern region was higher than in the northern region (Fig. 2c). The general distribution of the
179 stratification index was similar to that of surface salinity because it tended to be high in areas where
180 surface salinity was low. The surface mixed layer (Z_m) was thinner than 15 m over the entire study area
181 (Fig. 2d). In the study area, the depths of nitracline (Z_{nit}) ranged from 2.5 m to 35 m (Fig. 2e), with a
182 mean nitracline depth of 12.8 ± 7.7 m.

183

184 3.2. Nutrient distribution

185 Since the mean depths of euphotic zone in this study was about 30 m, the distribution of ambient
186 nutrient concentrations integrated from surface in the upper to 30 m of the water column are-is shown in
187 Fig. 3. The concentrations of nitrite+nitrate ranged from 21.51 to 355.43 mmol m⁻², whereas the
188 ammonium concentration ranged from 15.36 to 109.51 mmol m⁻² (Figs. 3a and 3b). High nitrite+nitrate

189 concentrations that exceeded 200 mmol m^{-2} were observed at the center of the CL section (Fig. 3a). The
190 ambient concentrations of these nutrients in the southern region ($134.15 \pm 98.41 \text{ mmol m}^{-2}$ for
191 nitrite+nitrate and $61.22 \pm 20.55 \text{ mmol m}^{-2}$ for ammonium, respectively) were approximately two times
192 higher than their concentrations in the northern region ($75.01 \pm 52.01 \text{ mmol m}^{-2}$ for
193 nitrite+nitrate and $40.49 \pm 20.69 \text{ mmol m}^{-2}$ for ammonium) (see Table 2). The concentration of phosphate
194 in the study area was fairly uniform, with a mean of $24.03 \pm 8.30 \text{ mmol m}^{-2}$ (Fig. 3c). The silicate
195 concentration was generally higher in the southern region than in the northern region (Fig. 3d).

196

197 3.3. Chlorophyll *a* concentration

198 The distribution of the chlorophyll *a* concentration in the upper 30 m (i.e., mean depth of euphotic
199 zone in this study) of the entire study area is shown in Fig. 4. High chlorophyll *a* concentrations of over
200 80 mg m^{-2} were observed in the western side of the CL section (from st. CL5 to st. CL8), and low
201 chlorophyll *a* concentrations were shown in the western side of the CS section (Fig. 4). The highest
202 concentration (286.4 mg m^{-2}) was obtained at station CL8. Over the entire study area, the mean
203 chlorophyll *a* concentration integrated from the surface to 30 m was 42.7 mg m^{-2} ($\text{SD} = \pm 57.4 \text{ mg m}^{-2}$).
204 The average concentrations were 21.7 mg m^{-2} ($\text{SD} = \pm 19.6 \text{ mg m}^{-2}$) and 54.5 mg m^{-2} ($\text{SD} = \pm 67.7 \text{ mg m}^{-2}$)
205 for the northern and southern regions, respectively.

206

207 *3.4. Primary production rates*

208 Overall, the hourly carbon production rates integrated over the euphotic zone from six light depths
209 ranged from 1.1 to 108.6 mg C m⁻² h⁻¹, with a mean of 27.7 mg C m⁻² h⁻¹ (SD = 34.7 mg C m⁻² h⁻¹). The
210 highest primary production rates were found at station CL8 (108.6 mg C m⁻² h⁻¹) followed by station
211 CL5A (82.1 mg C m⁻² h⁻¹) (Fig. 5). In the northern region, the carbon production rates ranged from 1.1 to
212 18.7 mg C m⁻² h⁻¹, with a mean of 9.0 mg C m⁻² h⁻¹ (SD = ± 6.4 mg C m⁻² h⁻¹). In comparison, the average
213 rates in the southern region were approximately five times higher than the average rates in the northern
214 region (43.3 ± 41.7 mg C m⁻² h⁻¹).

215 The vertically integrated nitrate production rates ranged from 0.14 to 18.77 mg NO₃ m⁻² h⁻¹, with a
216 mean of 2.72 mg N m⁻² h⁻¹ (SD = ± 5.51 mg N m⁻² h⁻¹), whereas the ammonium production rates ranged
217 from 1.16 mg NH₄ m⁻² h⁻¹ to 16.16 mg NH₄ m⁻² h⁻¹, with a mean of 4.66 mg NH₄ m⁻² h⁻¹ (SD = ± 4.38 mg
218 NH₄ m⁻² h⁻¹) (Fig. 6). The total nitrogen (nitrate+ammonium) production rates ranged from 1.31 mg N m⁻²
219 h⁻¹ to 34.94 mg N m⁻² h⁻¹, with a mean of 7.38 mg N m⁻² h⁻¹ (SD = ± 9.71 mg N m⁻² h⁻¹). At most stations
220 except for stations of CL8 and CS8R, the ammonium production rates were generally higher than the
221 nitrate production rates (Fig. 6). The average nitrate production rate was 0.41 mg NO₃ m⁻² h⁻¹ (SD = ±
222 0.51 mg NO₃ m⁻² h⁻¹) in the northern region, whereas the average nitrate production rate for the southern
223 region was 4.64 mg NO₃ m⁻² h⁻¹ (SD = ± 7.13 mg NO₃ m⁻² h⁻¹). In comparison, the average ammonium
224 production rates for the northern and southern regions were 2.56 mg NH₄ m⁻² h⁻¹ (SD = ± 1.74 mg NH₄

225 $\text{m}^{-2} \text{h}^{-1}$) and $6.41 \text{ mg NH}_4 \text{ m}^{-2} \text{ h}^{-1}$ ($\text{SD} = \pm 5.28 \text{ mg NH}_4 \text{ m}^{-2} \text{ h}^{-1}$), respectively.

226

227 3.5. Statistical analysis of environmental variables according to geographic regions

228 One-way analysis of variance (ANOVA) was performed to assess significant regional differences in
229 the environmental and biological variables of the two geographic regions (i.e., northern and southern).

230 One-way ANOVA revealed significant regional differences for some of the environmental and biological
231 variables in the study area (Table 2). The temperature and salinity of the surface were significantly

232 different due to the effects of various water masses in the region. The stratification also exhibited a

233 significant regional variability due to the higher accumulation of freshwater in the southern region ($p <$

234 0.05). However, the mean mixed layer depths were not significantly different, with means of 7.6 m ($\text{SD} =$

235 $\pm 2.8 \text{ m}$) and 8.4 m ($\text{SD} = \pm 2.4 \text{ m}$) for the northern and southern regions, respectively (Table 2). The

236 mean depths of nitracline were similar between the regions, although there were differences between the

237 stations. The ambient nutrient concentrations of the upper 30 m showed highly significant differences,

238 with higher concentrations in the southern region, although the phosphate concentration was not

239 significantly different between the regions (Fig. 3 and Table 2). In addition, the chlorophyll *a*

240 concentrations were significantly different ($p < 0.05$), with a value that was approximately two times

241 higher in the southern region than in the northern region.

242

243 *3.6. FWC distribution*

244 To understand the potential effects of recent changes in the FWC on the primary production in the
245 Chukchi Sea, the FWC data obtained from the three RUSALCA expeditions were used for a comparison.
246 In 2012, the FWC in the study area were ranged from 2.1 to 8.5 m, with a mean of 4.5 m ($SD = 1.2$ m)
247 (Fig. 7a). The strongest freshwater accumulation was observed in the western side of the CS section and
248 north of the Herald Canyon ($FWC = 6.7-8.5$ m), whereas the lowest freshwater accumulation was
249 observed at the center of the CL section in the southern region ($FWC = 2.8-3.7$ m) (Fig. 7a). The FWC in
250 2009 ranged from 2.6 to 11.8 m, with a mean of 5.1 m ($SD = \pm 1.7$ m) (Fig. 7b). The mean value in 2009
251 was a little higher than that of 2012 due to the high accumulation of FWC from the East Siberian Sea and
252 the region north of Herald Canyon (Fig. 7b). In 2009, the FWC in the southern region was evenly
253 distributed with an accumulation of below 6 m. In 2004, the mean FWC was 4.7 ± 1.3 m and ranged from
254 2.0 to 9.9 m (Fig. 7c). Unlike the observations from 2012 and 2009, the FWC in the southern region in
255 2004 indicated a low accumulation in the western side and a progressive increase in FWC toward the
256 eastern side (Fig. 7c).

257

258 **4. Discussion**

259 *4.1. Regional carbon and nitrogen production rates in 2012*

260 In this study, there were large differences in the carbon and nitrogen production rates the between

261 southern and northern regions (Figs. 5, 6 and Table 2). The average rate of carbon production in the
262 southern region was about five times higher than that of the northern region (Fig. 5 and Table 2).
263 Similarly, the total nitrogen (nitrate+ammonium) production rates were approximately four times higher
264 in the southern region than in the northern region (Fig. 6). In particular, the regional differences were
265 much higher for the nitrate production rate than the ammonium production rate (Table 2). We also found
266 that the carbon production rates obtained from all of the RUSALCA expeditions (2004, 2009 and 2012)
267 showed highly significant differences between the regions ($p < 0.001$, $n = 43$) (data not shown).

268 The regional differences in phytoplankton production rates may have resulted from the different
269 environmental conditions, as revealed the statistical analysis (Table 2). Especially, the different nutrient
270 conditions and thereby different phytoplankton biomasses may be an important reason for the regional
271 differences in the production rates of phytoplankton, since there was a positive relationship between the
272 ambient nutrient concentrations (nitrate) and the chlorophyll *a* concentrations integrated from surface to
273 30 m ($r = 0.6468$, $p < 0.0001$, $n = 41$) (Fig. 8a). Moreover, we found that the carbon, nitrate and
274 ammonium production rates were significantly correlated with the chlorophyll *a* concentration ($r = 0.9234$,
275 $r = 0.9641$ and $r = 0.9798$, $p < 0.0001$, $n=11$, respectively) (Fig. 8b). Even though the regional differences
276 in temperature are quite similar to that in primary production rates, there was no significant relationship
277 between temperature and primary production rates in this study. According to Gosselin et al. (1997), the
278 latitudinal variability in the phytoplankton production and biomass were primarily regulated by changes

279 in the surface ice cover and the depths of the surface mixed layer, which determine the amount of light
280 available to the phytoplankton in the water column. However, this was not the case in our study, as the
281 mixed-layer depths were not significantly different between the southern and northern regions of the
282 Chukchi Sea (Table 2).

283 The production/biomass ratio (P/B ratio), which was calculated by dividing the daily carbon
284 production rate ($\text{mg C m}^{-2} \text{ d}^{-1}$) by the integrated chlorophyll *a* concentration (mg chl-a m^{-2}), in the southern
285 region ($9.61 \pm 4.26 \text{ mg C (mg chl-a)}^{-1} \text{ d}^{-1}$) was somewhat higher than the P/B ratio in the northern region
286 ($5.46 \pm 1.27 \text{ mg C (mg chl-a)}^{-1} \text{ d}^{-1}$). This result indicated better carbon production efficiency by the
287 phytoplankton in the southern region. Therefore, the regional differences in the primary production rates
288 may have been affected by different production efficiencies in addition to the different phytoplankton
289 biomasses induced under different nutrient conditions.

290

291 4.2. Primary production rate in 2012 compared to the previous RUSALCA expeditions

292 Based on a 15-hour photo period in the Chukchi Sea (Hansell and Goering 1990; Lee et al. 2007; Yun
293 et al. 2014) and the hourly carbon production rates measured in this study, in 2012, the daily carbon
294 production rates integrated from the surface to 1 % light depth ranged from 0.02 to 1.61 $\text{g C m}^{-2} \text{ d}^{-1}$. The
295 daily carbon production rate in 2012 (mean \pm SD = $0.42 \pm 0.52 \text{ g C m}^{-2} \text{ d}^{-1}$), which was averaged from the
296 values from all the productivity stations, was quite similar to the daily carbon production rate of 2004

297 (mean \pm SD = 0.41 ± 0.53 g C m⁻² d⁻¹) reported by Lee et al. (2007). The production rates (mean \pm SD =
298 0.26 ± 0.24 g C m⁻² d⁻¹) obtained in 2009 and presented by Yun et al. (2014) were significantly lower than
299 those from 2012 and 2004, which is believed to be due to the different sampling times among the three
300 cruises because the seasonal variation in primary productivity is quite large in this region (Springer and
301 McRoy 1993; Wang et al. 2005; Hill et al., 2013). These differences in the primary production rates
302 obtained by the three cruises also may have been due to interannual variations in primary productivity in
303 the Chukchi Sea, as Hirawake et al. (2012) used satellite remote sensing data obtained from 2002 to 2010
304 to show that the Chukchi Sea experiences strong interannual variation in August and September.

305 In 2012, the average daily carbon production rates were 0.66 g C m⁻² d⁻¹ (SD = ± 0.62 g C m⁻² d⁻¹) in
306 the southern region and 0.14 g C m⁻² d⁻¹ (SD = ± 0.10 g C m⁻² d⁻¹) in the northern region. By comparison,
307 the average daily carbon production rates in the southern and northern regions were 0.57 g C m⁻² d⁻¹ (SD
308 = ± 0.64 g C m⁻² d⁻¹) and 0.16 g C m⁻² d⁻¹ (SD = ± 0.18 g C m⁻² d⁻¹) in 2004, respectively, and 0.38 g C m⁻²
309 d⁻¹ (SD = ± 0.26 g C m⁻² d⁻¹) and 0.14 g C m⁻² d⁻¹ (SD = ± 0.16 g C m⁻² d⁻¹) in 2009, respectively. From
310 the regional comparisons, we found that the pattern of primary production in the Chukchi Sea is largely
311 different depending on regions. The primary production rates in the northern region were consistently low,
312 since the regionally low nutrient conditions and phytoplankton biomass. Thus, they were not largely
313 changed among the three cruises. In contrast, the primary production rates for the southern region were
314 considerably variable among the three cruises, although they including seasonal and interannual

315 variations. Since this study revealed that the nutrient is an important factor in controlling primary
316 production, the recent change in primary production for the southern region could be induced by changes
317 in nutrient conditions in the region. The changes in freshwater inputs in the region may have been closely
318 related to the nutrient and primary production variability (detailed in section 4.3).

319

320 *4.3. The effects of FWC on the nutrients and primary production in the southern Chukchi Sea*

321 FWC plays an important role in determining the nutrient distribution/inventory and, therefore, the
322 availability of nutrients for phytoplankton growth in the Arctic Ocean. Coupel et al. (2015) showed that
323 the strong freshening of the Canada Basin resulted in the deepening of the nitracline, which had a
324 negative impact on primary production. In addition, Yun et al. (2014) reported that the low primary
325 production rate in the Chukchi Sea could be due to the decreases in the nutrient and chlorophyll *a*
326 concentrations that resulted from the increased input of fresh waters. In 2012, we found that the
327 freshwater had strongly accumulated in the western side of the southern Chukchi Sea and especially in the
328 CS section (Fig. 7a) due to an inflow of fresh Siberian Coastal Water or sea ice meltwater. This could
329 have resulted in the low primary production rates observed in the western region and the CS section of the
330 southern Chukchi Sea (Fig. 5). In contrast, relatively high production rates were observed in the center of
331 the CL section, the region with the lowest accumulation of freshwater (Figs. 5 and 7a). The strong inflow
332 of Siberian Coastal Water from the East Siberian Sea into the Chukchi Sea was also found in 2009,

333 though it was not detected in 2004 (Figs. 7b and 7c). These inputs of freshwater presumably influenced
334 the nutrient reservoir and its replenishment from deep waters ([e.g. Canada Basin](#))-(Coupel et al., 2015),
335 eventually driving the observed changes in primary production in the region. Based on data obtained from
336 southern region during three cruises, we found that FWC had a significant negative effect on the nitrate
337 concentrations ($r = 0.5363$, $p < 0.05$) and primary production rates ($r = 0.5645$, $p < 0.05$) (Figs. 9a and 9b).
338 As a result, the primary production rates in the Chukchi Sea could be highly significantly correlated with
339 the nitrate concentrations ($r = 0.7482$, $p < 0.001$) (Fig. 9c). Therefore, we might conclude that the primary
340 production in the Chukchi Sea could be primarily controlled by nutrient availability related to FWC
341 variability, as reported in previous studies conducted in different regions of the Arctic Ocean (Tremblay
342 and Gagnon, 2009; Tremblay et al., 2002, 2006, Coupel et al., 2015). However, the influence of ocean
343 circulations should be examined further because the ocean circulation such as pacific inflow and Beaufort
344 Gyre can redistribute the amount of freshwater (Giles et al., 2012), eventually leading to regional
345 differences in FWC (Giles et al., 2012; Morison et al., 2012). Additionally, we need to consider the local
346 wind field, as the spatial distribution of FWC is largely dependent on the wind and is controlled by
347 atmospheric pressure patterns (Anderson et al., 2011).

348

349 *4.4. Current status of the primary production in the Chukchi Sea*

350 To understand the recent status of primary production in the Chukchi Sea, the *in situ* measurements of

351 primary production in the region in recent years were plotted with those from the previous studies in
352 decades ago (Fig. 10). The average carbon production rate from the three RUSALCA cruises in the
353 Chukchi Sea was $0.33 \text{ g C m}^{-2} \text{ d}^{-1}$ (SD = $0.40 \text{ g C m}^{-2} \text{ d}^{-1}$). In addition, Hill ~~et al.~~ and Cota (2005) reported
354 that the mean daily production rate during the initial ice breakup was $0.8 \text{ g C m}^{-2} \text{ d}^{-1}$ in 2002. The daily
355 production rates obtained by Lee et al. (2012) and Lee et al. (2013) were 0.54 and $0.86 \text{ g C m}^{-2} \text{ d}^{-1}$,
356 respectively (Fig. 10). Even though the different sea ice condition could affect difference in the
357 productivity. These recent measurements of primary production (Hill ~~et al.~~ and Cota 2005; Lee et al.,
358 2007, 2012 and 2013; Yun et al., 2014; This study) showed significantly lower rates compared with the
359 previously reported rates from the region (Hameedi, 1978; Korsak, 1992; Zeeman, 1992) $(t\text{-test, } p <$
360 $0.01)$. Moreover, it is obviously shown a decreasing trend of primary production ($r = 0.7689, p < 0.01$)
361 (Fig. 10).

362 This is very interesting because primary production could be expected to increase in the region due to
363 the increased light availability to the phytoplankton. For example, based on satellite ocean color data,
364 Arrigo et al. (2008) found large increases in the annual net primary production on the continental shelves
365 of the Chukchi Sea as well as Siberian and Laptev seas due to increased open water areas and longer
366 growing seasons. However, the *in situ* measurements of primary production in recent years (Hill ~~et al.~~ and
367 Cota 2005; Lee et al., 2007, 2012 and 2013; Yun et al., 2014; This study) have shown consistently lower
368 primary production rates compared to those in previous studies.

369 The strong seasonal and interannual variation in the region could be suggested for reason causing the
370 low primary production, as discussed above. Hill et al. (2013) found that the seasonal variations in
371 primary production in the southern Chukchi Sea peaked in July and then progressively declined in August
372 and September. In fact, the lowest primary production rates given by Yun et al. (2014) were obtained from
373 the late summer season (i.e., from 1 to ~~31~~30, September, 2009) compared with the rates found in the
374 present study (from ~~27-30~~ August to ~~16-14~~ September, 2012) or in Lee et al. (2007) (from ~~10-11~~ to 22
375 August, 2004). In comparison, previous studies (Hameedi, 1978; Korsak, 1992; Zeeman, 1992) included
376 the measurements obtained from July to August (Fig. 10). However, their measurements just starting from
377 the end of July were mostly done during August (Korsak, 1992; Zeeman, 1992). Although recent
378 measurements from the three RUSALCA cruises (2004, 2009 and 2012) may not have reflected the
379 highest values (i.e., July) of primary production, the measurements from Hill ~~et al.~~ and Cota (2005) or Lee
380 et al. (2012 and 2013) include the values in the mid-July and early August. Therefore, the recent low rates
381 of primary production might be reflected by decreasing trend rather than results of seasonal and
382 interannual variations.

383 More plausible reason for the recent low primary production in the Chukchi Sea could be due to the
384 decreased concentrations of nutrients and chlorophyll *a*. According to Whitledge and Lee (unpublished
385 data), in recent years, there have been significant decreases of 30-50% in nutrient concentrations and
386 approximately 40% in the integrated chlorophyll *a* concentration in the Bering Strait and the Chukchi Sea.

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387 Based on the significant relationships between primary production and the nutrient and FWC (discussed
388 in section 4.3), the recent decrease in nutrient and chlorophyll *a* concentrations may have been closely
389 related to the changes in freshwater inputs in the region. According to Serreze et al. (2006), there was
390 recently larger import of freshwater through the Bering Strait compared with previous estimates.
391 Therefore, the recent decreases in the concentrations of major inorganic nutrients and chlorophyll *a* may
392 have resulted in lower primary production rates in the Chukchi Sea.

393 Recently, the freshwater content in the Arctic Ocean, which includes river discharge, pacific water
394 inflow through the Bering Strait, sea ice melt water and net precipitation (Jones et al., 2008), has
395 increased over the past few decades. If the increased freshwater content in the Chukchi Sea are
396 continuously observed, the Chukchi Sea might have become less productive region compared with
397 previous decades.

398

399 **5. Conclusions**

400 This study reported the regional characteristics of primary production in the Chukchi Sea and recent
401 trend of primary production based on *in situ* measurements. The different nutrient conditions and
402 phytoplankton biomass could be an important reason for the regional differences in the production rates
403 of phytoplankton. Based on comparison between previous studies in decades ago and recent
404 measurements, we found that recent primary production in the Chukchi Sea showed a decreasing trend.

405 The changes in freshwater inputs in the region may have been closely related to the nutrient and primary
406 production variability. Although Coupel et al. (2015) reported that the recent freshening of the Arctic
407 Ocean does not significantly affect primary production in the Chukchi shelf based on comparison with
408 measurements in the deep Canada Basin, our results showed that the freshwater variability in the Chukchi
409 Sea has had a large influence on the recent changes in primary production by controlling the nutrient
410 inventory. If the increased freshwater inflow persists, the primary production in the region will
411 considerably decrease, ultimately resulting in changes in the regional characteristics of primary
412 production. However, a large interannual variability of primary production remains despite the statistical
413 significance observed in this study. Therefore, more measurements under various environmental
414 conditions are needed to better understand the recent variations in the primary production in the Chukchi
415 Sea. In particular, there could be some changes in the phytoplankton community structures because the
416 smaller cells benefit more than the larger cells under increased freshening conditions (Li et al., 2009).

417

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425

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Figure Legends

Fig. 1. Locations of sampling stations during the 3rd-2012 RUSALCA expedition in the Chukchi Sea ~~in~~ 2012. The primary production rates were measured at the stations identified by blue circles. The st. CS8R location represents a revisit to st. CS8.

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Fig. 2. The distribution of surface temperature [T_{sur}][°C] (a), surface salinity [S_{sur}] (b), stratification index [$\Delta\sigma_t$][kg m⁻³] (c), surface mixed layer depth [Z_m][m] (d), and nitracline depth [Z_{nit}][m] (e) during the 2012 RUSALCA.

Fig. 3. The distributions of the integrated concentrations of ambient nitrite+nitrate [NO_2+NO_3][mmol m⁻²] (a), ammonium [NH_4][mmol m⁻²] (b), phosphate [PO_4][mmol m⁻²] (c), and silicate [SiO_4][mmol m⁻²] (d) ~~in the water column (up to from surface to -30 m)~~ during the 2012 RUSALCA.

Fig. 4. The ~~integrated~~ chlorophyll *a* concentrations ~~in the water column (integrated from surface up to 30 m)~~ [mg m⁻²] during the 2012 RUSALCA.

Fig. 5. Hourly carbon uptake rates [mg C m⁻² h⁻¹] integrated from the surface to 1% light depth during the 2012 RUSALCA.

Fig. 6 Hourly nitrate and ammonium uptake rates [mg N m⁻² h⁻¹] integrated from the surface to 1% light depth during the 2012 RUSALCA.

Fig. 7. The distributions of Fresh Water Content (FWC in m) in the Chukchi Sea in 2012 (a), 2009 (b) and 2004 (c).

Fig. 8. Relationships between nitrate concentrations (mmol m⁻²) and chlorophyll *a* concentrations (mg m⁻²) integrated from surface to 30 m (a) (n = 41); chlorophyll *a* concentrations (mg m⁻²) and daily carbon (g C m⁻² d⁻¹) and nitrogen production rate (mg N m⁻² d⁻¹) over the euphotic zones (b) (n = 11). All data obtained

during the 2012 RUSALCA.

Fig. 9. Relationships between FWC (m) and nitrate concentrations (mmol m^{-2}) (a); FWC (m) and daily primary production rate ($\text{g C m}^{-2} \text{d}^{-1}$) (b); nitrate concentrations (mmol m^{-2}) and daily primary production rate ($\text{g C m}^{-2} \text{d}^{-1}$) (c). All data obtained from southern region during the three RUSALCA cruises.

Fig. 10. A recent trend of primary production based on *in situ* carbon uptake measurements (^{13}C or ^{14}C) in the Chukchi Sea.

Table 1 Location, water depth (m) and euphotic depth (Z_{eu}) for primary productivity stations in the Chukchi Sea in 2012.

Region	Station	Date (mm/dd/yr)	Location		Depth (m)	Z_{eu} (m)
			Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ W)		
Northern	CEN4	09/05/12	69.9828	-175.6857	63	34
	CEN1A	09/06/12	70.7085	-178.2988	38	20
	HC2	09/07/12	70.9000	-175.0127	74	36
	HC26	09/08/12	71.7878	-174.3945	55	46
	G12	09/11/12	71.3980	-171.2597	55	46
Southern	CS8	08/30/12	67.4312	-169.6030	51	24
	CS17	09/01/12	68.2983	-167.0418	40	22
	CL5A	09/02/12	68.6407	-170.9423	59	20
	CL3R	09/12/12	69.0048	-168.9000	57	26
	CL8	09/13/12	67.8692	-172.5482	53	24
	CS8R	09/14/12	67.4312	-169.6030	51	26

Table 2 Summary of one-way analysis of variance (ANOVA) for environmental variables in two geographic regions of the Chukchi Sea in 2012. The mean values (ranges in parentheses) and their significant differences (> or <) between northern and southern regions are given for surface temperature (T_{sur}), surface salinity (S_{sur}), stratification index ($\Delta\sigma_t$), surface mixed layer depth (Z_m), nitracline depth (Z_{nit}), fresh water content (FWC), nitrite+nitrate concentration of the upper 30 m (NO_2+NO_3), ammonium concentration of the upper 30 m (NH_4), phosphate concentration of the upper 30 m (PO_4), silicate concentration of the upper 30 m (SiO_4) and chlorophyll *a* concentration of the upper 30 m (Chl-*a*). *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$, ns: not significant. $n = 52$. Also given are mean and range values for carbon production (CP), nitrate production (NP) and ammonium production (AP) (all $mg\ C\ or\ N\ m^{-2}\ d^{-1}$). $n=11$.

Variables	Northern		Southern
T_{sur} ($^{\circ}C$)	0.62 (-1.33 ~ 4.13)	<***	3.89 (1.60 ~ 8.53)
S_{sur}	29.27 (27.30 ~ 32.04)	>*	27.48 (21.48 ~ 32.35)
$\Delta\sigma_t$ ($kg\ m^{-3}$)	3.15 (0.79 ~ 5.34)	<*	4.47 (0.71 ~ 9.71)
Z_m (m)	7.6 (4.0 ~ 14.0)	ns	8.4 (4.0 ~ 14.0)
Z_{nit} (m)	13.0 (2.5 ~ 30.0)	ns	12.6 (2.5 ~ 35.0)
NO_2+NO_3 ($mmol\ m^{-2}$)	75.01 (21.51 ~ 218.22)	<*	134.15 (21.82 ~ 355.43)
NH_4 ($mmol\ m^{-2}$)	40.49 (15.36 ~ 86.93)	<***	61.22 (28.54 ~ 109.51)
PO_4 ($mmol\ m^{-2}$)	22.19 (5.43 ~ 34.26)	ns	25.95 (8.30 ~ 43.57)
SiO_4 ($mmol\ m^{-2}$)	245.49 (104.79 ~ 800.49)	<***	410.86 (129.17 ~ 669.94)
Chl- <i>a</i> (mg/m^{-2})	21.7 (2.2 ~ 69.3)	<*	54.5 (3.1 ~ 286.4)
CP ($mg\ C\ m^{-2}\ d^{-1}$)	134.7 (16.3 ~ 280.7)		649.1 (151.3 ~ 1628.9)

NP (mg N m ⁻² d ⁻¹)	6.1 (2.2 ~ 19.9)	69.7 (4.5 ~ 281.6)
AP (mg N m ⁻² d ⁻¹)	38.4 (17.4 ~ 83.6)	96.2 (45.0 ~ 242.4)