REPLY TO REVIEWER #1

We thank the reviewers and the associate editor for their constructive comments. We have addressed the comments by reviewer #1 (as detailed below) and have revised the manuscript accordingly. Please note that page and line numbers in the reviewer's comments refer to the original manuscript while our references to page and line numbers refer to the revised manuscript.

Specific comments: Page 3, Lines 49-52: Hill et al., 2005 → Hill and Cota, 2005, Arrigo et al., 2015 → Arrigo and van Dijkend, 2015, Bélanger et al., 2013 → Bélanger et al., 2008?, Wassmann and Slagstad, 2011 → Wassmann et al., 2011. Please check references throughout the text!!

We thank the reviewer for pointing out the mistakes in reference list. We have thoroughly checked and revised.

Page 3, Line 60: McLaughlin and Carmack, 2010 → McLaughlin et al., 2010

Corrected

Page 4, Line 70: Bélanger et al., 2013 → check the reference!

This reference is added in the reference list of the revised manuscript.

Page 4, Line 74: Vancoppenolle et al., 2013 → this citation is no in reference list!

This reference is added in the reference list of the revised manuscript.

Page 5, Line 94: Does your measured carbon uptake correspond to NPP or primary production? You need consistency for that throughout the text. Otherwise, you need to define NPP.

The present study addressed only small phytoplankton uptake rates measured on the basis of a 4hrs *in situ* incubation experiments. Hence, the data do not represent net primary production. To make sure the consistency we removed the term net primary production from the manuscript.

Page 6, Line 132: "The chlorophyll (chl) samples" → Does it mean the chlorophyll a? Or does it contain chlorophyll a, b, and c? Kind of confused in the text!

We used Chl *a* for the present study. We have replaced "Chl" with "Chl *a*" in the revised manuscript.

Pages 6-7: In materials and methods section, there is no description for how to measure water temperature and salinity, although water temperature and salinity data are used in Table 1 and

28 described in the text. Please describe a detail method for the water temperature and salinity

29 measurement!

30 The temperature and salinity were measured using a Seabird SBE9plus CTD (conductivity-

31 temperature-depth tool) equipped with dual temperature (SBE3) and conductivity (SBE4) sensors.

32 The information regarding temperature and salinity measurements has been added to the revised

33 manuscript.

34 Page 7, Line 134: Lee et al.,2005 → Lee and Whitledge, 2005

35 Corrected

36 Page 7, Line 149: ″Niskin bottles attached to CTD″ → CTD spell out!

37 CTD stands for Conductance Temperature Depth device. We have added the full term in the

38 revised manuscript.

39 Page 8, Line 165: Slawyk et al. 1977 → Slawyk et al. (1977)

40 Corrected

41 Page 9, Lines 180-184: No unit for the salinity!

42 Salinity is measured in Practical Salinity Unit (PSU). Usually it is not mentioned particularly.

43 However, we added the unit of salinity in the revised manuscript as per the reviewer's suggestion.

44 Page 9, Line 182: When I read this sentence, I thought that you investigated for a late summer in

45 2013.

46 We agree with the reviewer and changed it in the revised manuscript.

47 Page 9, Lines 189-191: I think authors may need to redraw figure 2 because I don't know whether

48 the subsurface chlorophyll maximum actually exists in this figure. I think it is only the results of

49 some stations.

51 Figure 2. does not contain any chlorophyll data. We have plotted the depth profiles of C, NO_3^-,

52 and NH_4^+ uptake rates and explained about the subsurface maxima of uptake rates. We also revised

53 the two sentences (190-192) as given to make the idea more clear.

54 "Fig. 2 shows the depth profiles C, NO_3^-, and NH_4^+ uptake rates in the Laptev, Kara, and East

55 Siberian seas. Only a few stations showed significant subsurface maxima for the C, NO_3^-, and

56 NH_4^+ uptake rates during the present study where the rest of them exhibited no significant variation

57 throughout euphotic zone".

58   Page 9, Line 193: "Fig. 3 & 4" → Figs.

59   Corrected

60   Page 10, Line 211: Parkinson, 2002 → this citation is no in reference list!

61   Reference is added in the revised manuscript.

62   Page 11, Line 227: "Table 2, Fig. 3 & 4" → Figs.

63   Corrected

64   Page 11, Line 239: Kirk, 1983 → this citation is no in reference list!

65   Added to the reference list.

66   Page 11, Line 240: Shiklomanov, 2000 → Shiklomano et al., 2000

67   We have checked the reference, however, we found that Shiklomanov, 2000 is the correct version.

68   Page 12, Lines 252-258: "The depth-integrated NO_2^-+NO_3^- concentrations varied between"→

69   ". . .concentrations in the euphotic zone varied. . ..." You do not show euphotic zone depth. Add

70   euphotic zone depth in Table 1. If the difference in the depth of euphotic is large, the result may

71   be influenced in nutrients budget. Also, I think that the meaning of "high concentrations of

72   NO3+NO2 and phosphate" are ranked based on only nitrogen data and mentioned stations are not

73   special compared to other stations.

74   We agree to the reviewer's opinion regarding the influence of euphotic depth on depth integrated

75   nutrient budget. We have added euphotic depth details in Table 1. The euphotic depths observed

76   are different in almost all of the stations ranging from 33 to 76 m. However, the data from our

77   present study did not show any dependency of depth integrated nutrient budget with euphotic depth.

78   For example, AF019, Af080, and AF095 stations have deeper euphotic zone, however; they are

79   not having depth integrated NO_2^-+NO_3^- concentrations close to the highest values obtained at

80   AF068, AF071, and AF005 which are having relatively shallower euphotic depths. The depth

81   integrated P values also showed higher values at stations (AF019, AF068, AF100, AF080, AF095,

82   and AF091) with both deeper and shallower euphotic depths. Based these information we could

83   not derive any correlation between euphotic depths and nutrient budget. We have added one

84   paragraph to explain these findings in the revised manuscripts (lines: 303-312).

85 Page 12, Line 262: this the stations → what stations?

86 We have corrected the sentence in the revised manuscript as "In reference to the stations (AF005,

87 AF068, and AF071 in the Laptev Sea and AF100 in the Kara Sea) nearby the river inlets were

88 observed with relatively higher nutrient concentrations (Table 1)."

89 Page 12, Line 257: "Table 1, Fig. 3 & 4" → Figs.

90 Corrected.

91 Page 13, Line 268: "higher than those of present study area" → You do not show daily data for

92 carbon uptake rates! Add your data based on daily carbon uptake rates!

93 The reference which we used was for total primary production. So we revised that sentence with

94 small phytoplankton primary production data by Lee et al. (2017a). The revised sentence is as

95 follows. "In agreement to this, the small C uptake rates reported from the Chukchi Sea (58.6–194

96 mg Cm^{-1} d^{-1}; average = 127 ±55.2 mg Cm^{-1} d^{-1}); Lee et al., 2017a) was relatively higher than those

97 of present study (5.86-191mg C m^{-2}d^{-1}; average=37.7± 41.6)".

98 Page 13, Line 272: Glibert et al., 2011 → this citation is no in reference list!

99 Reference is added in the revised manuscript.

100 Page 13, Line 288: It is necessary to investigate whether there is a relationship between SST and

101 small phytoplankton uptake rate. You are dealing with an entirely different ecosystem as you

102 mentioned.

103 We appreciate the reviewer's opinion. The relationship of small phytoplankton DIN and C uptake

104 rates with SST was checked already. However, a significant relationship was not observed. It can

105 be possibly due to the narrow range of SST variation among the stations and also due to co-

106 influence of multiple environmental factors.

107 Page 14, Lines 290-293: "However, Fig. 5 show a weak,...." → Authors just stated that possibility

108 of small phytoplankton efficiency to peak at nutrient stoichiometry close to Redfield's ratio. In my

109 opinion, the DIN: P ratio of less than 16 means mainly nitrogen limitation in ocean. If DIN: P is

110 the degree of nitrogen limitation, it can be interpreted that small phytoplankton is just

111 advantageous to survive better than large. I wonder why the contribution of small phytoplankton

112 is below 50% despite of the nitrogen limitation. Why did this happen? I guess that DIN:P ratios

113   below 8 seem to affect the rate of phytoplankton uptake regardless of size based on limited data in

114   this study.

115   We agree with the reviewer's comment partially. It is possible that nutrient limitation can affect

116   the small phytoplankton potential to assimilate C and N. However, from our study we could

117   observe that the contributions were higher as 80% as well as lower as 25% at DIN:P below 8:1.

118   However, the average small phytoplankton contributions are above the global average. And also,

119   the results from the present study cannot claim that the lower DIN:P is the reason for lower

120   contributions of small phytoplankton to the total primary production. We have explained it in the

121   revised manuscript. Lines: 331-339 and 445-458

122   Page 14, Lines 299-300: "between small phytoplankton uptake are DIN:P" → "and" instead of "are"

123   Corrected as per the reviewer's suggestion.

124   Page 15, Line 316: "Fig. 6 & 7" → Figs.

125   Corrected.

126   Page 15, Line 323: Glibert et al., 1982 → Glibert, 1982

127   Corrected.

128   Page 15, Line 314: " the bottom water. . .. . ..(1000-1700 hours) turnover times compared to" →

129   ". . . turnover times for NH_4^+ substrate. . ." And what does mean bottom depth? Is it correspond to

130   1% light depth? Define the bottom depth in euphotic zone!

131   Checked and corrected as follows, Page 17: lines: 361-364

132   "Fig. 7 shows that turnover times for NH_4^+ substrate (within 500 hours) in the surface waters is

133   longer, however; relatively faster than NO_3^- in upper layers of euphotic zone in almost all the

134   stations in the Arctic Ocean. However, the bottom waters of euphotic zone showed relatively

135   longer (1000-1700 hours) turnover times for NH_4^+ substrate compared to the surface waters."-

136   Lines 368-373

137   Page 15, Line 316: "both NO3- and NH4+ substrates" → at surface water???? Or throughout the

138   euphotic zone?

139   Yes. Station AF044 showed consistently higher turnover times for both NH_4^+ and NO_3^- in the

140   surface waters. We have revised the sentence as follows "The sampling location in East Siberian

141 Sea (AF044) was observed with relatively longer turnover times for both NO_3^- and NH_4^+ substrates

142 at the surface layers (Figs. 6 & 7) possibly due to the lower uptakes rates over there".

143 Page 16, Line 339: "quantum efficiency/yield" → quantum efficiency (or quantum yield)

144 By "/" we meant "or" here. To avoid the confusion we replaced "efficiency/yield" by only "yield"

145 in the revised manuscript. We also modified the sentence as "The quantum yield for the present

146 study is defined as the uptakes of DIN (NO_3^- +NH_4^+ uptake rates) and C by unit small

147 phytoplankton Chl *a* fraction which is obtained by dividing uptake rates by Chl *a* concentrations".

148 Page 16, Line 341: "in Fig. 8 and 9" → Figs.

149 Corrected.

150 Page 16, Lines 355-356: Wassmann and Slagstad, 2011 → Wassmann et al., 2011, Tremblay et

151 al., 2002 → this citation is no in reference list! Please check the reference!

152 Corrected.

153 Page 17, Line 374: Legendre et al. (1993) →1992?, check the reference! Please, double check and

154 correct them, if needed.

155 Checked and corrected as per the reviewer's suggestion. It is Legendre et al., 1992.

156 Page 17, Line 375: "large phytoplankton cells (45µm)" → check the cell size. I think it probably

157 means > 5 µm.

158 We apologize for the typo mistake. We have corrected it to >5µm in the revised manuscript.

159 Page 29, Fig. 2: Rephrase legend for Fig. 2

160 Corrected.

161

162

163

164

165

166

167

168   REPLY TO REVIEWER #2

169

170   We thank the reviewers and the associate editor for their constructive comments. We have

171   addressed the comments by reviewer #2 (as detailed below) and have revised the manuscript

172   accordingly. Please note that page and line numbers in the reviewer's comments refer to the

173   original manuscript while our references to page and line numbers refer to the revised manuscript.

174   Some missing references and incorrect ones, e.g., Hill and Cota, 2005, Arrigo et al., 2015,

175   McLaughlin and Carmack, 2010, and more. Authors need to check the references throughout the

176   text.

177   We have checked the references thoroughly and edited as per the reviewer's suggestions.

178   The list of new references are given below,

179   Agawin, N.S., Duarte, C.M. and Agustí, S.: Nutrient and temperature control of the contribution
180   of picoplankton to phytoplankton biomass and production. Limnol. Oceanogr., 45(3), pp.591-600,
181   2000.
182   Aksnes, D. L. and Egge, J. K.: A theoretical model for nutrient uptake in phytoplankton. Mar. Ecol.
183   Prog. Ser. , 70, 65–72, 1991.
184   Clasby, R.C., Horner, R. and Alexander, V.: An in situ method for measuring primary productivity
185   of Arctic sea ice algae. J. Fish. Res. Board Can., 30(6), pp.835-838,1973.
186   Eppley, R. W. and Thomas, W. H.: Comparison of half-saturation constants for growth and nitrate
187   uptake of marine phytoplankton. J. Phycol., 5, 375–379, 1969.
188   Grover, J. P.: Influence of cell shape and size on algal competitive ability. J. Phycol. , 25, 402–
189   405, 1989.
190   Grover, J. P.: Resource competition in a variable environment: phytoplankton growing according
191   to the variable-internal-stores model. Am. Nat. , 138, 811–835, 1991.
192   Harrison, W.G. and Cota, G.F.: Primary production in polar waters: relation to nutrient availability.
193   Polar Res., 10(1), pp.87-104, 1991.
194   Hein, M., Folager Pedersen, M. and Sand-Jensen, K.: Size-dependent nitrogen uptake in micro-
195   and macroalgae. Mar. Ecol. Prog. Ser. , 118, 247–253, 1995.
196   Horner, R. and Schrader, G.C.: Relative contributions of ice algae, phytoplankton, and benthic
197   microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic, pp.485-503,
198   1982.
199   Irwin, A.J, Zoe V. F, Oscar M. E. Schofield, Falkowski, P.G.: Scaling-up from nutrient physiology
200   to the size-structure of phytoplankton communities, J. Plank. Res., 28 (5), 459–471, 2006.
201   Joo, H., Son, S., Park, J.W., Kang, J.J., Jeong, J.Y., Kwon, J.I., Kang, C.K. and Lee, S.H.: Small
202   phytoplankton contribution to the total primary production in the highly productive Ulleung Basin
203   in the East/Japan Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr., 143, pp.54-61, 2017.
204   Kirk, J. T. O.: Light and Photosynthesis in the Aquatic Ecosystems, Cambridge Univ. Press,
205   Cambridge, U. K., 1983.

206 Sakshaug, E. and Holm-Hansen, O.: Factors governing pelagic production in polar oceans. In
207 Marine phytoplankton and productivity (pp. 1-18). Springer, Berlin, Heidelberg, 1984.
208 Shuter, B. G.: Size dependence of phophorus and nitrogen subsistence quotas in unicellular
209 microrganisms. Limnol. Oceanogr., 23, 1248–1255, 1978.
210 Tremblay, J.É., Gratton, Y., Carmack, E.C., Payne, C.D. and Price, N.M.: Impact of the large-scale
211 Arctic circulation and the North Water Polynya on nutrient inventories in Baffin Bay. J. Geophys.
212 Res.: Oceans, 107(C8), pp.26-1, 2002.
213 Vancoppenolle, M., Meiners, K.M., Michel, C., Bopp, L., Brabant, F., Carnat, G., Delille, B.,
214 Lannuzel, D., Madec, G., Moreau, S. and Tison, J.L.: Role of sea ice in global biogeochemical
215 cycles: emerging views and challenges. Quaternary science reviews, 79, pp.207-230, 2013.
216 Yun, M.S., Whitledge, T.E., Stockwell, D., Son, S.H., Lee, J.H., Park, J.W., Lee, D.B., Park, J.
217 and Lee, S.H., Primary production in the Chukchi Sea with potential effects of freshwater content.
218 Biogeosciences, 13(3), pp.737-749, 2016.

219 Line 97, The major rivers flows in to the Arctic.. Change with flow into the Arctic.

220 Changed as per the reviewer's suggestion.

221 Line 109, ..a first.. Change with the first.

222 Changed as per the reviewer's suggestion.

223 No detail description for the measurements for water temperature and salinity in materials and

224 methods.

225 We have added the information regarding temperature and salinity measurement in the revised

226 manuscript as follows. "The temperature and salinity were measured using a Seabird SBE9plus

227 CTD (conductivity-temperature-depth tool) equipped with dual temperature (SBE3) and

228 conductivity (SBE4) sensors". Lines 129-130

229   Line 132, The chlorophyll (chl) samples... chlorophyll a? or chlorophyll a, b, and c?

230 We have used Chl *a* for the present study and the manuscript is revised by replacing Chl with Chl

231 *a?*

232 Line 140, C and N uptake rates.. C and DIN uptake rates?

233 By "N" we meant "DIN". To avoid confusion we have replaced "N" with "DIN" in the revised

234 manuscript.

235 Line 151, light filters.. What kind of light filters?

We have used neutral density light filters (LEE filters) to cover the polycarbonate sample bottles.

The details have added in the revised manuscript. Line 154

Line 165, the methods Slawyk et al., 1977.. Check the sentence!

We have revised the sentence as per the reviewer's suggestion. Lines 175-178

Line 191, a subsurface maxima like most of global ocean.. You need add some related references

for that!

Since we did not get references for depth profiles of small phytoplankton uptake rates, we revised

the sentence without reference. We reframed the sentence to avoid confusion as follows,

"Fig. 2 shows the depth profiles C, NO_3^-, and NH_4^+ uptake rates per hour in the Laptev, Kara, and

East Siberian seas. Only a few stations showed significant subsurface maxima for the C, NO_3^-, and

NH_4^+ uptake rates during the present study where the rest of them exhibited no significant variation

throughout euphotic zone". Lines 193-197

-Line 194, The depth integrated.. Make a consistency with depth integrated inline 192

Replaced "depth integrated" with "depth-integrated" throughout the manuscript as per the

reviewer's suggestion.

Line 197, the maximum small plankton. . . small phytoplankton?

It is "small phytoplankton". The correction has been done in the revised manuscript.

Line 197-198, How about any explanation for the maximum uptake rates at AF09?

The exceptionally high uptake rates for C, NO_3^-, and NH_4^+ obtained at station AF019 is indeed

very interesting. We observed very high particulate organic carbon as well as nitrogen

concentration and specific small phytoplankton uptake rates compared to other stations. However,

chlorophyll concentrations for the small phytoplankton community did not show such higher

values when compared to other stations. Based on the background data obtained during the present

259 study could not give a possible reason to the high uptake rates. We assume that the higher

260 metabolic rates can be due to presence of different autotrophic communities which are different

261 from other sampling locations. Unfortunately, we could not obtain species identification data

262 during the present study. Lines 205-213.

263 Line 219-220, any related reference?

264 As per the reviewer's suggestion we have added references for the contribution of ice algae to the

265 primary production. Clasby et al., 1973 and Horner and Schrader, 1982

266 Line 227-228, higher C and DIN uptake rates of what? Small phytoplankton or total phytoplankton?

267 We meant small phytoplankton uptake rates here. We apologize for the confusion.

268 -Line 231, lower C and DIN uptake rates of what? Small phytoplankton or total phytoplankton?

269 ⇒ very confused!!

270 We meant small phytoplankton uptake rates here. The manuscript is revised accordingly to remove

271 the ambiguities regarding small and total uptake rates. We attempted to compare with the small

272 phytoplankton uptake rates obtained from various regions in the revised manuscript.

273 Line 236, metabolic activities of phytoplankton. Small phytoplankton?

274 Yes. It is small phytoplankton. We have edited it in the revised manuscript.

275 -Line 237, Not much discussion for small phytoplankton primary production in 3.4 section!! You

276 need to focus more on small phytoplankton primary production.

277 We have attempted to explain more about the small phytoplankton uptake mechanism and

278 influence of nutrient concentrations on the small cells. Since there are not many experiments

279 conducted on small phytoplankton uptake rates, particularly from polar oceans, the comparative

280 analysis is relatively difficult. However, we attempted to give a better explanations in the revised

281 manuscript using the available resources. Lines 257-276 and 331-339.

282   -Line 253-254, make a same digit for concentrations.

283   We would like to keep 3 significant digits for the nutrients. In that case 22.3 and 189 are having

284   same significant digits that is 3. We believe that this representation is statistically correct. With

285   reviewer's permission we would like to keep the data same as it is.

286   -Line 258, check the sentence!

287   We have changed the sentence appropriately as per the reviewer's comment.

288   -Line 263, this the stations. which stations you mean?

289   We have revised the sentence with station details (AF005, AF068, and AF071 in the Laptev Sea

290   and AF100 in the Kara Sea) as per the reviewer's suggestions. Line 313

291   -Line 271, lower C and DIN uptake rates of What? Small or total phytoplankton?

292   We meant small phytoplankton uptake rates here. Revised the manuscript as per the reviewer's

293   suggestions.

294   -Line 279-282, Is this for only small phytoplankton contribution? You need to discuss more on

295   small phytoplankton primary production.

296   N starving can abstain both large and small phytoplankton from achieving potential primary

297   production. However, to an extent small phytoplankton are less severely affected by nutrient

298   limitation than large phytoplankton. Since the small phytoplankton cell size is small nutrient

299   requirement to gain potential primary production is relatively lower compared to the larger

300   phytoplankton cells. However, under very poor nutrient conditions, small phytoplankton may also

301   undergo nutrient starving.

302   We have explained it as follows in the revised manuscript: "In general, experimental and

303   theoretical evidences suggest that smaller cells have higher rates of nutrient uptake per unit

304   biomass and lower half-saturation constants due to their higher surface area to volume ratios

305 (Eppley and Thomas, 1969; Aksnes and Egge, 1991; Hein et al., 1995). And hence, the lower

306 minimum cellular metabolic requirement for small phytoplankton selectively allows them to

307 survive under lower resource concentrations than larger cells (Shuter, 1978; Grover, 1991). And

308 hence, small phytoplankton cells appear to have substantial leads over larger phytoplankton cells

309 under nutrient-limited steady-state environmental conditions (Grover, 1989; Grover, 1991).

310 However, under very poor nutrient conditions, small phytoplankton may also undergo nutrient

311 starving". Lines : 331-339

312 -Line 308, plankton to facilitate.. phytoplankton or zooplankton?

313 It is phytoplankton. We edited the sentence in the revised manuscript.

314 -Line 327-329, Are the results for turnover time in India for small phytoplankton? Or total

315 phytoplankton? If these results for total phytoplankton, then is it appropriate to compare turnover

316 rates for small phytoplankton in this study?

317 We appreciate the reviewer's concern. The turnover rates from India is of total phytoplankton

318 community. We admit that it is not wise to compare the turnover times by total phytoplankton with

319 those of small phytoplankton. However, as far as we know there are only few studies reported

320 turnover rates of total phytoplankton. Moreover, there is no report so far regarding the small

321 phytoplankton turnover rate measurements. Lines 381-396

322 -Line 339, ..quantum efficiency/yield.. What "/" means?

323 By "/" we meant "or" here. To avoid the confusion we replaced "efficiency/yield" by only "yield"

324 in the revised manuscript. We also modified the sentence as "The quantum yield for the present

325 study is defined as the uptakes of DIN (NO_3^- +NH_4^+ uptake rates) and C by unit small

326 phytoplankton Chl *a* fraction which is obtained by dividing uptake rates by Chl *a* concentrations".

327 –Line 343, it should be like this, ..C and N were observed..

328 Corrected

329 -Line 345-346, N yield.. Is this term correct?

330   We have replaced "N yield" with quantum yield for DIN" and the same done for "C quantum

331   yield".

332   -Line 350-351, check the sentence!

333   We have revised the sentence as given, "It is a known fact that the impact of global warming on

334   the Arctic Ocean has been introduced rapid changes in its physicochemical properties. Hence, the

335   necessity to trace the changes in primary production pattern in the Arctic Ocean gained attention

336   in the recent era".

337   -Line 373, Should be "the total primary production (Hodal and Kristiansen, 2008)."

338   Corrected.

339   -Line 376, .large phytoplankton cells (45µm). Is this size correct? Check the cell size

340   We apologize for the typo error. It is actually >5µm. The correction has been done in the revised

341   manuscript.

342

343

344

345

346

347

348

349

350

351

352

353 **The list of relevant changes done in the revised manuscript:**

354 We have checked the references thoroughly and edited as per the reviewer's suggestions.

355 The list of new references are given below

356 Agawin, N.S., Duarte, C.M. and Agustí, S.: Nutrient and temperature control of the contribution
357   of picoplankton to phytoplankton biomass and production. Limnol. Oceanogr., 45(3), pp.591-
358   600, 2000.
359 Aksnes, D. L. and Egge, J. K.: A theoretical model for nutrient uptake in phytoplankton. Mar. Ecol.
360   Prog. Ser. , 70, 65–72, 1991.
361 Clasby, R.C., Horner, R. and Alexander, V.: An in situ method for measuring primary productivity
362   of Arctic sea ice algae. J. Fish. Res. Board Can., 30(6), pp.835-838,1973.
363 Eppley, R. W. and Thomas, W. H.: Comparison of half-saturation constants for growth and nitrate
364   uptake of marine phytoplankton. J. Phycol., 5, 375–379, 1969.
365 Grover, J. P.: Influence of cell shape and size on algal competitive ability. J. Phycol. , 25, 402–
366   405, 1989.
367 Grover, J. P.: Resource competition in a variable environment: phytoplankton growing according
368   to the variable-internal-stores model. Am. Nat. , 138, 811–835, 1991.
369 Harrison, W.G. and Cota, G.F.: Primary production in polar waters: relation to nutrient availability.
370   Polar Res., 10(1), pp.87-104, 1991.
371 Hein, M., Folager Pedersen, M. and Sand-Jensen, K.: Size-dependent nitrogen uptake in micro-
372   and macroalgae. Mar. Ecol. Prog. Ser. , 118, 247–253, 1995.
373 Horner, R. and Schrader, G.C.: Relative contributions of ice algae, phytoplankton, and benthic
374   microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic, pp.485-
375   503, 1982.
376 Irwin, A.J, Zoe V. F, Oscar M. E. Schofield, Falkowski, P.G.: Scaling-up from nutrient physiology
377   to the size-structure of phytoplankton communities, J. Plank. Res., 28 (5), 459–471, 2006.
378 Joo, H., Son, S., Park, J.W., Kang, J.J., Jeong, J.Y., Kwon, J.I., Kang, C.K. and Lee, S.H.: Small
379   phytoplankton contribution to the total primary production in the highly productive Ulleung
380   Basin in the East/Japan Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr., 143, pp.54-61, 2017.
381 Kirk, J. T. O.: Light and Photosynthesis in the Aquatic Ecosystems, Cambridge Univ. Press,
382   Cambridge, U. K., 1983.
383 Sakshaug, E. and Holm-Hansen, O.: Factors governing pelagic production in polar oceans. In
384   Marine phytoplankton and productivity (pp. 1-18). Springer, Berlin, Heidelberg, 1984.
385 Shuter, B. G.: Size dependence of phophorus and nitrogen subsistence quotas in unicellular
386   microrganisms. Limnol. Oceanogr., 23, 1248–1255, 1978.
387 Tremblay, J.É., Gratton, Y., Carmack, E.C., Payne, C.D. and Price, N.M.: Impact of the large-scale
388   Arctic circulation and the North Water Polynya on nutrient inventories in Baffin Bay. J.
389   Geophys. Res.: Oceans, 107(C8), pp.26-1, 2002.
390 Vancoppenolle, M., Meiners, K.M., Michel, C., Bopp, L., Brabant, F., Carnat, G., Delille, B.,
391   Lannuzel, D., Madec, G., Moreau, S. and Tison, J.L.: Role of sea ice in global biogeochemical
392   cycles: emerging views and challenges. Quaternary science reviews, 79, pp.207-230, 2013.
393 Yun, M.S., Whitledge, T.E., Stockwell, D., Son, S.H., Lee, J.H., Park, J.W., Lee, D.B., Park, J.
394   and Lee, S.H., Primary production in the Chukchi Sea with potential effects of freshwater
395   content. Biogeosciences, 13(3), pp.737-749, 2016.

396

397 We have added more explanation regarding small phytoplankton uptake metabolism as follows

398 (Lines : 331-339):

399 "In general, experimental and theoretical evidences suggest that smaller cells have higher rates of

400 nutrient uptake per unit biomass and lower half-saturation constants due to their higher surface

401 area to volume ratios (Eppley and Thomas, 1969; Aksnes and Egge, 1991; Hein et al., 1995). And

402 hence, the lower minimum cellular metabolic requirement for small phytoplankton selectively

403 allows them to survive under lower resource concentrations than larger cells (Shuter, 1978; Grover,

404 1991). And hence, small phytoplankton cells appear to have substantial leads over larger

405 phytoplankton cells under nutrient-limited steady-state environmental conditions (Grover, 1989;

406 Grover, 1991). However, under very poor nutrient conditions, small phytoplankton may also

407 undergo nutrient starving".

408

409

410

411

412

413

414

415

416

417

418

419   **MARKED MANUSCRIPT**

420

421   **First *in situ* estimations of small phytoplankton carbon and nitrogen uptake rates in the Kara,**

422   **Laptev, and East Siberian seas**

423   P. S. Bhavya.[1], Jang Han Lee[1], Ho Won Lee[1], Jae Joong Kang[1], Jae Hyung Lee[1], Dabin Lee[1], So

424   Hyun Ahn[1], Dean A. Stockwell[2], Terry E. Whitledge[2], Sang Heon Lee[1*]

425

426   *correspondence to: Sang Heon Lee (*sanglee@pusan.ac.kr*)

427

428   [1]Department of Oceanography, Pusan National University, Busan 609-735, Korea
429   [2]Institute of Marine Science, University of Alaska, Fairbanks, AK 99775, USA

430

431

432

433

434

435

436

437

438

439   **Abstract.** Carbon (C) and nitrogen (N) uptake rates by small phytoplankton (0.7-5 μm) in the Kara,

440   Laptev, and East Siberian seas in the Arctic Ocean were quantified using *in situ* isotope labelling

441   experiments for the first time as a part of the NABOS (Nansen and Amundsen Basins

442   Observational System) program during August 21-September 22, 2013. The depth-integrated C,

443   nitrate (NO_3^-), and ammonium (NH_4^+) uptake rates by small phytoplankton showed a wide range

444   from 0.54 to 15.96 mgC $m^{-2}h^{-1}$, 0.05 to 1.02 mgC $m^{-2}h^{-1}$, and 0.11 to 3.73 mgN $m^{-2}h^{-1}$, respectively.

445   The contributions of small phytoplankton towards the total C, NO_3^-, and NH_4^+ were varied from

446   25 to 89%, 31 to 89%, and 28 to 91%, respectively. The turnover times for NO_3^- and NH_4^+ by

447   small phytoplankton during the present study point towards the longer residence times (years) of

448   the nutrients in the deeper waters, particularly for NO_3^-. Relatively, higher C and N uptake rates

449   by small phytoplankton obtained during the present study at locations with less sea ice

450   concentration point toward the possibility of small phytoplankton thrive under sea ice retreat under

451   warming conditions. The high contributions of small phytoplankton toward the total carbon and

452   nitrogen uptake rates suggest capability of small size autotrophs to withstand in the adverse

453   hydrographic conditions introduced by climate change.

454

455

456   *Key Words*: The Arctic Ocean, nitrogen, carbon, and small phytoplankton.

457

458

459

1. Introduction

The Arctic Ocean has been always a key attraction for the oceanic expeditions due to its rapid response to changing environmental conditions caused by both natural and anthropogenic factors. It has been reported that the rate of decrease in sea ice extent in the Arctic Ocean is significantly high and eventually caused a decline in sea ice thickness over recent decades (Stroeve et al., 2008; Comiso et al., 2008; Kwok et al., 2009; Overland and Wang, 2013). As an immediate effect, sea ice retreat would benefit the primary production by autotrophs due to increased exposure to sunlight (Hill and Cota, 2005; Gradinger, 2009; Arrigo et al., 2012, Arrigo and van Dijken, 2015; Bélanger et al., 2008; Kahru et al., 2016). It was also reported that primary production in the Barents Sea showed an increase by 30% during the warm period (1989-1995) than the cold one during 1960s (Wassmann et al., 2011; Arrigo et al., 2008). However, as a result of sea ice melting, the ice-algal communities can be replaced by pelagic communities. Although, ice-algal communities are not a large contributor towards the primary production, their absence could potentially alter vertical flux of organic carbon and coupling between the euphotic and benthic zones (Walsh, 1989).

Sea surface warming can also result in a strong water column stratification which can reduce nutrient supply to the surface water and consequently a decrease in primary production (Bopp et al., 2001; Lee et al., 2007, 2012; Tremblay and Gagnon, 2009; Li et al., 2009; Martin et al., 2010; McLaughlin et al., 2010; Steinacher et al., 2010; Slagstad et al., 2011; Thomas et al., 2012) and thus alterations in C dynamics in the Arctic Ocean (Arrigo et al., 2008; Bates and Mathis, 2009; Cai et al., 2010). It has been a debatable topic that how phytoplankton communities in the Arctic Ocean would respond to the physical, chemical, and biological stress introduced by global warming. One group of researchers have reported that there has been an enhancement in the annual

483   primary production due to increased light availability and warmer temperature in the Arctic Ocean

484   (Arrigo et al., 2008; Arrigo and Dijken, 2011; Thomas et al., 2012). However, another group

485   suggested that excess moisture fluxes under warmer sea conditions can introduce wider cloud

486   covers during summer and early fall and thus, the possibility of reduction in autotrophic primary

487   production is inevitable (Eastman and Warren, 2010; Vavrus et al., 2012; Bélanger et al., 2013).

488   Water column stratification is also a contrary effect introduced by the global warming which can

489   significantly reduce the vertical mixing of nutrient rich deep waters and that can lower primary

490   productivity (Tremblay and Gagnon, 2009; Lee et al., 2007, 2012; Yun et al., 2015). On other hand,

491   decline in nutrient concentrations in the surface waters while sustained levels in the deeper waters,

492   could be an immediate effect of global warming (Vancoppenolle et al., 2013). Such environment

493   would be adverse for the large phytoplankton communities whose nutrient requirements are higher

494   for achieving potential primary production level (Li et al., 2009). However, small phytoplankton

495   (size range: 0.7-5 μm), which have lower nutrient requirements, are found to be proliferated under

496   such conditions (Li et al., 2009; Daufresne et al., 2009). Hence, understanding the mechanism and

497   processes of small phytoplankton metabolic activities under various environmental conditions

498   would be a crucial aspect of the Arctic Ocean ecosystem research.

499   There have been few studies conducted to understand the fate of small phytoplankton under

500   changing environmental scenario (Li et al., 2009; Yun et al., 2015). They identified that the

501   smallest phytoplankton cells can flourish under such nutrient replete conditions, however; the

502   larger cells decline (Li et al., 2009). And hence, the reduction in community average body size of

503   the autotrophs is expected to be an obvious response to the global warming (Daufresne et al., 2009).

504   Consequently, the primary production assisted by the small phytoplankton would be a substantial

505   part of the Arctic Ocean biogeochemistry. However, the contribution of small phytoplankton

506 towards the autotrophic C and dissolved inorganic nitrogen [here; DIN= $NO_3^- + NH_4^+$] fixation

507 has been one of the least investigated topics in the global ocean research, particularly in the Arctic

508 Ocean (Semiletov et al., 2005; Arrigo and Dijken, 2011; Hill et al., 2017; Yun et al., 2012, 2015;

509 Lee et al., 2007, 2012).

510 Apart from global warming, localized influences are also an important factor in controlling the

511 primary production in the Arctic Ocean. It has been reported that the Arctic Ocean

512 biogeochemistry is mainly governed by the high riverine as well as intrusions of Atlantic and

513 Pacific waters (Shiklomanov et al., 2000; Carmack and Macdonald, 2002; Peterson, et. al., 2002;

514 Anderson et al., 2004). The major rivers flow into the Arctic Ocean are the Ob', Lena, Yenisey,

515 and Mackenzie, and numerous smaller ones in both the Amerasian and Eurasian sectors. It is

516 reported that the Ob' and Yenisey Rivers show an increase in their fresh water discharge since

517 1980s (Semiletov et al., 2005; Anderson et al., 2009). These seas situate along the continental shelf

518 of the Arctic Ocean which is known to be the widest and shallowest shelf in the world oceans

519 (Semiletov et al., 2005). These seas are characterized by highly dynamic organic matter production

520 and export to the deeper ocean as well as profound atmospheric exchange of volatile gases

521 (Semiletov et al., 2005; Anderson et al., 2009).

522 There were few studies conducted to estimate the influence of river effluences on C and DIN

523 uptake rates (Lee et al., 2007, 2012; Yun et al., 2015). However, the potential impact of riverine

524 influx on small phytoplankton uptake rates, very relevant for accountability of natural and

525 anthropogenic influences on the Arctic primary production, were not have been subjected to

526 investigation so far. The present study reports the first investigation results on small phytoplankton

527 (size: 0.7-5 μm) contribution towards the C, NO_3^-, and NH_4^+ uptake rates in the Kara, Laptev, and

528 East Siberian seas. Considering the global relevance of the Arctic Ocean biogeochemistry, the

529 present study aimed at the (1) estimation of small phytoplankton contribution towards the total

530 primary production as well as NO_3^- and NH_4^+ uptake rates and (2) investigation on various factors

531 influencing the small phytoplankton community efficiency in the Kara, Laptev, and East Siberian

532 Seas.

533 **2. Materials and Methods**

534 **2.1. Study Area**

535 The investigations on biochemical parameters and C and DIN transformation rates in the Kara,

536 Laptev, and East Siberian seas were conducted at 19 monitoring stations selected from a total of

537 116 NABOS stations (Fig. 1; Table 1). The geographical boundaries of each sea were defined as

538 per the classification done by Pabi et al. (2008) (Fig. 1). Based on this classification, there were 4,

539 13, and 2 stations were located in the Kara, Laptev, and East Siberian seas. The Kara and East

540 Siberian seas have surface areas almost two times (926×10^3 km^2 and 987×10^3 km^2, respectively)

541 larger than the Laptev Sea (498×10^3 km^2) (Jakobsson, 2001). Also, the Laptev and East Siberian

542 seas hold the shallowest zones of the Arctic Ocean basin with a mean depth of 48 m, where the

543 Kara Sea has a mean depth of 131 m (Jakobsson, 2001).

544 **2. 2. Sampling**

545 The sampling was conducted during 21^{st}August to 22nd September, 2013 onboard the Russian

546 vessel "*Akademik Fedorov*". The temperature and salinity were measured using a Seabird

547 SBE9plus CTD (conductivity-temperature-depth tool) equipped with dual temperature (SBE3) and

548 conductivity (SBE4) sensors. Samples for major inorganic nutrients [NO_3^-, nitrite (NO_2^-), NH_4^+,

549 phosphate (P), and silicate (Si)] were collected using Niskin bottles attached to the CTD device

550 and analysis was performed onboard using an Alpkem Model 300 Rapid Flow Nutrient Analyzer

551 (5 channels) based on Whitledge et al. (1981). The chlorophyll *a* (Chl *a*) samples for the small

552 phytoplankton fraction were obtained from 3 light depths (100, 30, and 1%). The preparation of

553 Chl *a* samples was based on the standard procedure reported in the previous studies (Lee and

554 Whitledge, 2005; Lee et al., 2012). Water samples for small Chl *a* fractions were sequentially

555 filtered through 5μm Nucleopore and then 0.7μm pore-sized Whatman GF/F filters (47 mm).

556 Further, the GF/F filters were wrapped in aluminum foil and kept frozen at -80 °C until the analysis.

557 During the analysis, the Chl *a* fractions from the filters were extracted using 90% acetone treatment

558 at –5°C for 24 hours. The extracted Chl *a* samples were undergone spectrophotometric analysis on

559 board using a pre-calibrated Turner Designs model 10-AU fluorometer. Samples for the C and

560 DIN uptake rates were collected from six *in situ* depths of light levels (100, 50, 30, 12, 5, and 1%)

561 determined at each station by the use of euphotic depth on the basis of Lambert-Beer's law.

562 Underwater PAR sensor (and/or optical instruments) could not be used due to logistic problems

563 and the euphotic depth was calculated using the Secchi depth which is a widely used method (Son

564 et al., 2005; Tremblay et al., 2000; Lee et al. 2012; Bhavya et al., 2016; 2017; Lee et al., 2017a,

565 2017b).

2.3 ^{13}C and ^{15}N labeling experiments

567 The estimation of C and DIN uptake rates were done using ^{13}C and ^{15}N duel isotope labeling

568 experiments (Dugdale and Goering, 1967; Slawyk et al 1977; Dugdale and Wilkerson, 1986).

569 Seawater samples at each light depth were collected using Niskin bottles attached to the CTD

570 Rosette and transferred to acid-cleaned polycarbonate incubation bottles (approximately 1 L)

571 wrapped with neutral density light filters (LEE filters) to match with desired light levels.

572 Immediately, samples were spiked with 98-99 % enriched tracer solutions of NaH^{13}CO$_3$, K^{15}NO$_3$,

573 or ^{15}NH$_4$Cl at concentrations of ~0.3 mM, ~0.8μM, and ~0.1μM for the estimations of C, NO$_3^-$,

574   and NH_4^+ uptake rates, respectively. Further, the samples were subjected to 4-6 hrs of incubation

575   in big transparent Plexiglas incubators on deck under natural light conditions with provided

576   running surface seawater. Immediately after the incubation, 0.3 L of incubated samples were

577   filtered through pre-combusted GF/F filters (25mm diameter) for the total uptake rate estimation.

578   The samples for small fraction, sub-samples (0.5 L) of the incubated waters were passed through

579   5 μm Nuclepore filters (47 mm) to remove large phytoplankton cells (>5 μm) and then the filtrate

580   was passed through pre-combusted GF/F (25 mm) for the small phytoplankton (Lee et al., 2013).

581   The values for large phytoplankton in this study were obtained from the difference between small

582   and total fractions (Lee et al., 2013). Samples were kept frozen (-20 °C) until the mass

583   spectrometric analysis (Finnigan Delta+XL) at the stable isotope laboratory of University of

584   Alaska Fairbanks, US. The uncertainties for $\delta^{13}C$ and $\delta^{15}N$ measurements were ±0.1‰ and ±0.3‰,

585   respectively. DIN uptake rates of small phytoplankton were estimated using the mathematical

586   formula given by Dugdale and Goering (1967).

587   DIN uptake rate = $P * \Delta I_p / (T * (I_0 S_a + I_r S_t) / (S_a + S_t) - I_0)$

588   Where: P is the amount of particulate N in the post incubation sample, ΔI_p is the increase in ^{15}N

589   atom% in particulate N during incubation, S_a and S_t are ambient and added NO_3^- (or NH_4^+)

590   concentrations, respectively, I_r and I_0 are ^{15}N atom% of added tracer and natural ^{15}N atom%, and

591   T is the incubation time period. This equation assumes no formation of nutrient during incubation

592   and therefore rates presented here are potential rates. Similarly, C uptake rates also were calculated

593   using the same equation where; P denotes the particulate organic C and S_a and S_t are ambient

594   dissolved inorganic carbon and added ^{13}C tracer concentrations, respectively. Ir and I_0 are ^{13}C atom%

595   of added tracer and natural ^{13}C atom%, respectively (Slawyk et al., 1977).

3. Results and discussions

3.1 Environmental parameters in the Arctic Ocean

The biological, chemical, and physical properties of the Arctic Ocean are mainly controlled by the circulation patterns governed by the Pacific and Atlantic Ocean waters (Anderson et al., 2004; Quadfasel, 2005) along with the river inputs (Peterson et al., 2002). The nutrient rich low saline (<33 PSU) Pacific Ocean waters and nutrient replete relatively more saline ($\approx$ 34.8 PSU) Atlantic Ocean waters collectively regulate the biogeochemical activities of the Arctic Ocean (Maslowski et al., 2004). The present study was conducted during late summer season where the sea surface temperature (SST) was ranged from –1.76 °C to 1.62 °C. The sea surface salinity (SSS) during the

study period varied from 28.29 to 33.44 PSU (Table 1) which could be due to the influence of both circulation pattern as well as fresh water inputs. The present study retrieved sea ice concentration (SIC) from National Snow & Ice Data Center obtained from 2013 cruise. The results show that the SIC has ranged from 0 % to 100 % (Table 1).

3.2 Carbon and nitrogen uptake rates by small phytoplankton

Fig. 2 shows the depth profiles C, NO_3^-, and NH_4^+ uptake rates per hour in the Laptev, Kara, and East Siberian seas. Only a few stations showed significant subsurface maxima for the C, NO_3^-, and NH_4^+ uptake rates during the present study where the rest of them exhibited no significant variation throughout euphotic zone. AF019 station showed an exceptionally higher C, NO_3^-, and NH_4^+ uptake rates, in general, with a sharp subsurface maxima. The depth-integrated C, NO_3^-, and NH_4^+ uptake rates by small phytoplankton in the East Siberian Sea were observed to be very low compared to those of other seas (Table 2, Figs. 3 & 4). The depth-integrated C uptake rates by small phytoplankton showed a wide range from 0.54 to 15.96 mg C $m^{-2}h^{-1}$. The depth-integrated

618   NO_3^- uptake rates ranged from 0.05 to 1.02 mg N $m^{-2}h^{-1}$, where NH_4^+ uptake rates varied from

619   0.11 to 3.73 mg N $m^{-2}h^{-1}$. The station AF019 showed the maximum small phytoplankton uptake

620   rates for C (15.96 mg C $m^{-2}h^{-1}$), NO_3^- (1.02 mg N $m^{-2}h^{-1}$), and NH_4^+ (3.73 mg N $m^{-2}h^{-1}$). The

621   contribution of small phytoplankton towards the total uptake is also very high at station AF019

622   (Table 2). The exceptionally high uptake rates for C, NO_3^-, and NH_4^+ obtained at station AF019 is

623   indeed very interesting. Similarly very high particulate organic carbon as well as nitrogen

624   concentration and specific small phytoplankton uptake rates compared to other stations were also

625   observed at station AF019. However, chlorophyll concentrations for the small phytoplankton

626   community did not show such higher values when compared to other stations. Based on the

627   background data obtained during the present study could not give a possible reason to the high

628   uptake rates. We assume that the higher metabolic rates can be due to presence of different

629   autotrophic communities which are different from other sampling locations. Unfortunately, we

630   could not obtain species identification data during the present study. The lowest C, NO_3^-, and NH_4^+

631   uptake rates were observed at AF044 and AF041. The highest SIC (100% and 60% at AF044 and

632   AF041, respectively) in this region might be a reason for lower primary productivity due to light

633   limitation.

634   **3.3 Sea ice and small phytoplankton primary production**

635   The previous investigations on SIC over the Arctic Ocean proved that, during winter, the high ice

636   formation leads to expelling of salt content to the surrounding water. This introduces a relatively

637   high saline as well as density water layer at the surface or just below the sea ice layer than

638   surrounding. Such condition leads to sinking of very cold and saline surface waters and

639   replacement by nutrient rich deeper water which is less dense and a little warmer. This process

640   leads to deep vertical mixing and replenishment of surface nutrient inventories (Niebauer et al.,

641 1990; Falk-Petersen et al., 2000). However, during spring, melting of sea ice results in a strong

642 surface ocean stratification where the nutrient-rich waters are being exposed to a light availability

643 to create favorable conditions for the phytoplankton growth (Kirk, 1983; Niebauer et al., 1990;

644 Falk-Petersen et al., 2000). It is also reported that the increasing atmospheric temperature due to

645 global warming has been considerably caused a reduction in SIC in the Arctic Ocean over the past

646 three decades, with a rapid decrease in recent years (Levi, 2000; Parkinson, 1999).

647 Since the ice cover has significant role in controlling primary production, the dynamics of SIC is

648 an integral part of the Arctic Ocean research (Arrigo et al., 2008; Ardyna et al., 2014; Kahru et al.,

649 2016). It has been reported that that the reduction in SIC would facilitate the photosynthetic activity

650 and increase CO_2 intake by the seas (Anderson and Kaltin, 2001; Bates et al., 2006; Kahru et al.,

651 2016). Apparently, it can cause a relative decline in the contribution by algae growing within the

652 sea ice (Subba Rao and Platt, 1984; Legendre et al., 1992; Gosselin et al., 1997), although sea ice

653 community contributes only less than 10% of the Arctic Ocean C sequestration (Clasby et al., 1973;

654 Horner and Schrader, 1982). A detailed study conducted on inter-annual variations in SIC and

655 primary production by Kahru et al. (2016) suggested that the primary production gets enhanced

656 with decline in SIC. Kahru et al. (2016) reported that decrease in SIC initially starts from June

657 onwards in the northeastern Barents Sea and between Greenland and the North American continent

658 with an increase in primary productivity. This extends to the Kara and Laptev seas during July-

659 August and these areas exhibit a gradual enhancement in primary productivity. Further, this

660 process migrates towards the off Siberia and eventually in the Beaufort and Chukchi seas. However,

661 the major enhancement of primary production generally occurs in the Laptev and Barents seas

662 (Kahru et al., 2016). In agreement to this, our results also show a relatively lower SIC and higher

663 small phytoplankton C and DIN uptake rates in the Laptev Sea region (Table 2, Figs. 3 & 4). The

664   maximum SIC in the Laptev Sea was observed at station AF071 which is 65%. The Kara Sea was

665   mostly void of ice cover and only one station (AF095) was observed with a SIC of 40%. Relatively

666   lower small phytoplankton C and DIN uptake rates were observed at both the stations in the East

667   Siberian Sea (AF041: 60% and AF044: 100%) where the SIC was observed to be the maximum

668   among all the stations. However, there was no significant inverse correlation of small

669   phytoplankton C and DIN uptake rates with SIC found during the present study (Figure not shown).

670   This could be due to influence of other environmental constraints such as low nutrients and

671   temperature on metabolic activities of small phytoplankton.

672   The investigations conducted in the Amundsen Sea, Antarctic Ocean reported that there is no

673   significant difference in small phytoplankton C uptake rates between polynya and non-polynya

674   regions. The depth integrated small phytoplankton C uptake rates obtained from polynya and non-

675   polynya regions in the Amundsen Sea were ranged from 58.6–193 mg C $m^{-2}d^{-1}$ (126 ± 55.2 mg C

676    $m^{-2}d^{-1}$) and 62.2– 266 mg C $m^{-2}d^{-1}$ (124 ± 69.3 mg C $m^{-2}d^{-1}$), respectively (Lee et al., 2017a).

677   These values show that depth integrated small phytoplankton C uptake rates reported from the

678   Amundsen Sea from both polynya and non-polynya regions are relatively higher than those

679   obtained from the Arctic Ocean during the present study (5.86-191mg C $m^{-2}d^{-1}$; Average=37.7±

680   41.6). The daily NO_3^- uptake rates of small phytoplankton obtained from the Amundsen Sea were

681   7.5–26.6 mg N $m^{-2}d^{-1}$ (16.7 ± 7.8 mg N $m^{-2}d^{-1}$) and 6.1–40.9 mg N $m^{-2}d^{-1}$ (20.1 ± 13.1 mg N

682    $m^{-2}d^{-1}$) and those of NH_4^+ uptake rates varied from 9.1–22.4 mg N$m^{-2}d^{-1}$ (15.8 ± 6.4 mg N $m^{-2}d$

683    $^{-1}$) and 9.9–81.1 mg N $m^{-2}d^{-1}$ (30.7 ± 24.5 mg N $m^{-2}d^{-1}$), respectively, for the non-polynya and

684   polynya regions. Similar to C uptake rates, small phytoplankton uptake rates for NO_3^- (0.75-12.2

685   mg N $m^{-2}d^{-1}$; 3.21±2.61 mg N $m^{-2}d^{-1}$) and NH_4^+ (2.68-69.3 mg N $m^{-2}d^{-1}$; average: 16.12±14.54

686   mg N $m^{-2}d^{-1}$) were also significantly lower than that of Amundsen Sea. The lower small

687 phytoplankton uptake rates in the Arctic waters compared to Antarctic waters can be possibility

688 due to the lower nutrient concentrations and co-limitation of N in the Arctic waters (Harrison and

689 Cota, 1991). Sakshaug & Holm-Hansen (1984) has reported that the maximum Arctic nutrient

690 concentrations are typically lower than minimum Antarctic concentrations.

691 **3.4 Nutrient sources and influence on small phytoplankton primary production**

692 The shallow water column depths and the existence of long coastline along with river runoff

693 provide a wide opportunity for the autotrophs in the Arctic Ocean to get sufficient light and

694 nutrients (Kirk, 1983). Also, the Arctic Ocean is known to be a large receptor of freshwater

695 discharge which exceeds 4000 km^3 per anum (Shiklomanov, 2000; Carmack and Macdonald,

696 2002). The riverine discharges may have a great role in keeping those stations nearby river inlet

697 distinctive in physico-chemical conditions. Similarly, the freshwater discharge from the six largest

698 Eurasian rivers increased by 7% during 1936 - 1999 (Peterson et al., 2002). Among the various

699 seas in the Arctic Ocean, the Kara and Laptev seas are known to be the first and second largest

700 receptors, respectively, of total organic carbon fluxes while the East Siberian Sea receives the least

701 (Rachold et al., 2000).

702 Nitrite+nitrate concentrations in most stations were observed to be homogeneous in the water

703 column up to a depth of 20 m (approximately 30% light depth); however, increased exponentially

704 towards the bottom waters (Figure not shown). The depth profiles of NH_4^+ and P did not show any

705 significant variation throughout the euphotic zone (Figure used in Lee et al., unpublished).

706 However, the nutrient concentrations were considerably distinct among the stations. The depth-

707 integrated $NO_2^-+NO_3^-$ concentrations varied between 22.3 and 189 mmol m^{-2}. The depth-

708 integrated concentrations of P and Si were ranged from 7.62 to 35.4 mmol m^{-2} and 19.5 to 308

709 mmol m^{-2}, respectively (Table 1). Generally, high concentrations of NO$_2^-$+NO$_3^-$ and phosphate

710 were found at AF005, AF068, and AF071 in the Laptev Sea and one station in the Kara Sea (AF100)

711 and they were relatively much higher than those of the East Siberian Sea (Table 1, Figs. 3 & 4).

712 However, the Si concentrations were higher in the East Siberian Sea in comparison with the other

713 two seas. These results are comparable with the earlier studies conducted by Codispoti and

714 Richards (1968). They suggested that the concentrations of P and NO$_3^-$ were so low as to indicate

715 nutrient limitation for phytoplankton production in the upper layers.

716 The details of euphotic depths and depth-integrated nutrient concentrations are shown in Table 1.

717 The euphotic depths observed are different in almost all of the stations ranging from 33 to 76 m.

718 However, the data from our present study did not show any dependency of depth- integrated

719 nutrient budget with euphotic depth. For example, AF019, AF080, and AF095 stations have deeper

720 euphotic zone, however; they are not having depth integrated NO$_2^-$+NO$_3^-$ concentrations close to

721 the highest values obtained at AF068, AF071, and AF005 which are having relatively shallower

722 euphotic depths. The depth-integrated P values also showed higher values at stations (AF019,

723 AF068, AF100, AF080, AF095, and AF091) with both deeper and shallower euphotic depths.

724 Hence, the variation in euphotic depths seems to be insignificant in determining the nutrient

725 budgets in the present study area.

726 In reference to the stations (AF005, AF068, and AF071 in the Laptev Sea and AF100 in the Kara

727 Sea) nearby the river inlets were observed with relatively higher nutrient concentrations (Table 1).

728 The sampling locations away from the river inputs are mostly invaded by the nutrient poor Atlantic

729 waters instead of nutrient rich Pacific water. In another way, the Pacific Ocean nutrient inputs are

730 generally restricted to the Chukchi Sea and the Amerasian Basin (Carmack et al., 1997; Dmitrenko

731 et al., 2006). It is worth noticing that all the sampling locations in the Arctic Ocean showed

732 significantly lower small phytoplankton C and DIN uptake rates possibly due to lack of light and

733 nutrients. The nutrient stoichiometry analyses suggested that the Arctic Ocean waters are N

734 starving and the N:P (here N = DIN: NO_2^-+NO_3^- + NH_4^+ and P: PO_4^{3-}) ratios are always below the

735 Redfield's ratio which is 16:1 (mol: mol) (Redfield, 1963; Sakshaug, 2004). The relative

736 abundances of micronutrients are also important factors to control the primary production (Glibert

737 et al., 2013; Bhavya et al., 2016, 2017). The DIN:P observed during the current study ranged from

738 2.60 to 16.4 with an average of 6.6 ± 3.0 which is also in agreement with the previous studies

739 reported. These ratios point towards the N-starvation of phytoplankton which can potentially

740 abstain them from growing to a bloom. It is reported that such cases with less nutrient

741 concentrations are generally less starving for small phytoplankton size range from 0.7-5 µm and

742 they appeared to be a dominant in the euphotic water columns (Lee and Whitledge, 2005; Li et al.,

743 2009; Yun et al., 2015).

744 In general, experimental and theoretical evidences suggest that smaller cells have higher rates of

745 nutrient uptake per unit biomass and lower half-saturation constants due to their higher surface

746 area to volume ratios (Eppley and Thomas, 1969; Aksnes and Egge, 1991; Hein et al., 1995). And

747 hence, the lower minimum cellular metabolic requirement for small phytoplankton selectively

748 allows them to survive under lower resource concentrations than larger cells (Shuter, 1978; Grover,

749 1991). And hence, small phytoplankton cells appear to have substantial leads over larger

750 phytoplankton cells under nutrient-limited steady-state environmental conditions (Grover, 1989;

751 Grover, 1991). However, under very poor nutrient conditions, small phytoplankton may also

752 undergo nutrient starving.

753

3.5 Nutrient co-limitation

Nutrient co-limitation is a major problem facing by marine phytoplankton in the oligotrophic as well as pelagic ecosystems. The recent studies suggested that the maximum uptake of phytoplankton generally occurs when nutrient stoichiometry is close to the Redfield's ratio which is 16:1 (Li et al., 2011; Glibert et al., 2013; Bhavya et al., 2016, 2017), irrespective of individual nutrient concentration. Since the present study dealt with a completely different ecosystems with high SIC, low nutrients and SSTs, understanding the influence of DIN:P would be challenging. In agreement to this, there was no significant correlations observed between C, NO_3^-, and NH_4^+ uptake rates with DIN:P during the present study. However, Fig. 5 shows a weak, although a positive correlation of small phytoplankton contribution towards with DIN:P. It indicates the possibility of small phytoplankton efficiency to peak at nutrient stoichiometry close to Redfield's ratio. However, the lack of sufficient stations with higher DIN:P values limits the present study from claiming the influence of nutrient stoichiometry on small phytoplankton contribution. It is also important to note that the stations are located at geographical locations with diverse hydrographical parameters. However, on the basis of few researches conducted from various parts of oceanic and estuarine regions, it is proven that DIN:P holds a strong control on total C and DIN uptake rates (Li et al., 2011; Glibert et al., 2013; Bhavya et al., 2016, 2017). Although there was no significant correlation obtained between small phytoplankton uptakes and DIN:P, the N co-limitation in the Arctic Ocean is clearly seen (Table 1). That means, the relative abundances of DIN and P are highly important for proper functioning of C and DIN uptake mechanism by autotrophs.

3.6 Turnover times of nutrients

The present study shows that DIN co-limitation persists in the Arctic Ocean can be one of the major problems which can potentially limits the small phytoplankton contribution. In that case, any inorganic N substrate introduced to the surface waters might be immediately used by the phytoplankton to facilitate the organic matter production under the favorable environmental conditions. The turnover time for any substrate is an important measurement to estimate how rapid an N substrate can be consumed. The estimation of turnover time is done by dividing substrate concentrations with corresponding uptake rates. Figs. 6 & 7 shows the turnover times for NO_3^- and NH_4^+ substrates when small phytoplankton communities are the only consumers exist. Fig. 7 shows that turnover times for NH_4^+ substrate (within 500 hours) in the surface waters is longer, however; relatively faster than NO_3^- in upper layers of euphotic zone in almost all the stations in the Arctic Ocean. However, the bottom waters of euphotic zone showed relatively longer (1000-1700 hours) turnover times for NH_4^+ substrate compared to the surface waters. The sampling location in East Siberian Sea (AF044) was observed with relatively longer turnover times for both NO_3^- and NH_4^+ substrates at the surface layers (Figs. 6 & 7) possibly due to the lower uptakes rates over there. Continuous supply of nutrients through rivers and less efficient DIN uptake rates might be major reasons for longer turnover times. Compared to NH_4^+, NO_3^- is consumed in distinctively longer periods as 14 folds at the surface waters and 25 folds in the bottom of euphotic zone. Primarily, such difference is due to the relative preference for NH_4^+ by the small phytoplankton and secondly due to the high concentrations of NO_3^- in the deep waters than NH_4^+ concentrations. The research outputs from a tropical eutrophic estuary in India has showed rapid turnover time (3.4 - 232 hrs for NH_4^+ and 7.13-2419 hrs for NO_3^-) by total phytoplankton communities for DIN substrates despite of higher nutrient concentrations (Bhavya et al., 2016). In general, inhibition for

799   NO_3^- uptake is a very common phenomenon when higher NH_4^+ concentrations occurs (e.g., Glibert,

800   1982; Harrison et al., 1987; McCarthy et al., 1999; Bhavya et al. 2016). It is also very likely to

801   have different turnover times with the similar DIN concentrations under different hydrographic

802   properties those can govern the C and DIN metabolism over there.

803   **3.7 Quantum yield**

804   During the present study, size-fractionated Chl *a* concentrations at three light levels (100, 30, and

805   1 %) were measured. The comparative analysis with the total Chl *a* fraction suggests that small

806   phytoplankton communities are major contributors in the Laptev, Kara, and East Siberian seas

807   (Figure not shown; data used from Lee et al. unpublished). The results showed significantly high

808   contributions of small phytoplankton towards the total Chl *a* at all the three light levels (63.3 (S.D.

809   = ±17.5%), 61.4 (S.D. = ±19.9%), and 59.0% (S.D. = ±18.4%) at 100, 30, and 1%, respectively).

810   The efficiency of Chl *a* in small phytoplankton communities to fix C and DIN is a matter of

811   concern in the Arctic Ocean. The quantum yield for the present study is defined as the efficiency

812   of unit Chl *a* in the small phytoplankton communities to fix DIN and C, which is calculated by

813   dividing uptake rates by Chl *a* concentration. The lower temperatures and salinities, ice cover, and

814   the poor light availability can potentially lower quantum yields. The quantum yield for C and DIN

815   are shown in Figs. 8 and 9, respectively. The maximum yields for both C and DIN were observed

816   at AF091 for 100 and 30 % light depths. However, the quantum yield for C at 1% light levels in

817   all the stations were observed to be very low more likely due to light limitation (Talling, 1957).

818   Although the quantum yield for DIN was lower at 1% in comparison with other two light levels

819   the drastic drop in quantum yield for DIN at the 1% light levels, like quantum yield for C, was not

820 observed. This can be due to the existence of significant NH_4^+ uptake rates in the light scarce

821 conditions.

3.8 Small and large phytoplankton contributions

823 It is a known fact that the impact of global warming on the Arctic Ocean has been introduced rapid

824 changes in its physicochemical properties. Hence, the necessity to trace the changes in primary

825 production pattern in the Arctic Ocean gained attention in the recent era. It has been reported that

826 the contribution of small phytoplankton towards the total C and DIN fixations would be increasing

827 under the warming conditions (Li et al., 2009, Thomas et al., 2012). A significant number of total

828 primary production estimates is available from the Arctic Ocean (Platt et al., 1982; Wassmann et

829 al., 2011; Vedernikov et al., 1994; Gosselin et al., 1997; Boetius and Damm, 1998; Tremblay et

830 al., 2002; Arrigo et al., 2008; Lee et al., 2007; 2012, 2017a; Arrigo and Dijken, 2011; Yun et al.,

831 2012, 2015; Kahru et al., 2016; Lee et al., unpublished). However, a deep understanding regarding

832 the boosting up of small phytoplankton under warming conditions and their contributions towards

833 the total primary production is still rudimentary.

834 The studies from the various oceanic bodies suggest that the small phytoplankton contribution to

835 the total annual C and DIN fixation varies between 20 to 65% (Agawin et al., 2000; Hodal and

836 Kristiansen, 2008; Joo et al. 2017; Lee et al. 2017a). The contributions of small phytoplankton to

837 total C uptake rates were significantly higher in the Amundsen Sea with an average of 50.8 %

838 (±42.8%) and 14.9 % (±8.4%), respectively, for the non-polynya and polynya regions (Lee et al.

839 2017a). The contributions of small phytoplankton to the total NO_3^- uptake rates were 28.2 %

840 (±15.9%) in the non-polynya region and 18.1 % (±6.8%) in the polynya region, respectively.

841 Similar to C assimilation rates, small phytoplankton contributions towards total NH_4^+ uptake rates

842 were higher in both non-polynya (52.8%: ±40.5%) and polynya (31.6%; ±10.1 %) regions(Lee et

843 al., 2017a). Similarly, small phytoplankton contribution in the western Canada basin in the Arctic

844 Ocean was reported to be 64% (Yun et al., 2015). A recent study from the Chukchi Sea reported

845 that the average contributions of small phytoplankton to C and total DIN uptake rates were

846 approximately 32% (S.D. = ±24%) and 37% (S. D. = ±26%), respectively (Lee et al., 2013).

847 Similar investigations conducted in the northern Barents Sea found that small phytoplankton

848 contributed almost half (46%) of the total primary production (Hodal and Kristiansen, 2008). The

849 MODIS-derived data in the Ulleung Basin from 2003 to 2012 suggested that the annual

850 contribution by small phytoplankton communities, in general, ranges from 19.6% to 28.4% with

851 an average of 23.6% (S.D. = ±8.1%) (Joo et al., 2017). This study suggested that the large

852 phytoplankton communities are the major contributors towards the primary production in the

853 Ulleung Basin. Similarly, Legendre et al. (1992) reported that primary production in the high-

854 latitude Arctic region waters, in general, was dominated by large phytoplankton cells (>5μm),

855 whereas the standing stock was dominated by small cell-sized phytoplankton (0.7–5 μm) due to

856 strong grazing stress on large cells.

857 The present study provides the first ever report on small phytoplankton contribution towards the

858 total primary production in the Kara, Laptev, and East Siberian seas in the Arctic Ocean. The

859 results from the study suggests that the small phytoplankton potentially contributed 24 to 89%, 32

860 to 89%, and 28 to 91 %, towards the total C, NO_3^-, and NH_4^+ uptake rates in the whole study region.

861 Large phytoplankton contributions (total-small phytoplankton contributions) towards the total

862 uptake rates obtained during the present study is given in Table 2. The assessments by Tremblay

863 et al. (2000) suggests that large phytoplankton can fix relatively more C per unit NO_3^- and thus

864 export more C than small phytoplankton. However, the results from the present study show that

865 the large phytoplankton communities in the Arctic Ocean could contribute only an average of 40%,

866   34%, and 35% towards the total C, NO_3^-, and NH_4^+ uptake rates, respectively. And hence, small

867   phytoplankton appears to be the major contributor of C, NO_3^-, and NH_4^+ uptake with percentage

868   contributions of 60%, 66% and 65%, respectively, in the Laptev, Kara, and East Siberian seas.

869   These values are much higher than the global average contribution (39%) of small phytoplankton

870   production assessed by Agawin et al. (2000).

871   **4. Conclusions**

872   The present study attempted to estimate small phytoplankton contributions towards the total C,

873   NO_3^-, and NH_4^+ uptake rates in the Kara, Laptev, and East Siberian seas. The contributions of

874   small phytoplankton towards the total C, NO_3^-, and NH_4^+ uptake rates ranged 25 - 89%, 31 - 89%,

875   and 28 –91%, respectively, in the Arctic Ocean. There was no significant influence of ice cover

876   on uptake rates was observed; however, the stations with high SIC were, in general, showed low

877   surface small phytoplankton uptake of C, NO_3^-, and NH_4^+. It is also observed that the DIN:P can

878   potentially play a major role in controlling the small phytoplankton contributions towards the DIN

879   uptake rates by small phytoplankton. The significant contributions of small phytoplankton indicate

880   their efficiency to withstand the hostile conditions such as low nutrients, changing SST, and high

881   ice cover. However, to understand influence of global warming on small phytoplankton activity,

882   growth, and community shift, long term *in situ* analyses as well as laboratory manipulations

883   experiments are highly recommended.

884

885

886

887

888

Acknowledgments

889

890   We thank the captain and crew of the *Akademik Fedorov* for their outstanding assistance during

891   the cruise. This research was supported by the Korea Research Foundation (KRF) grant funded by

892   the Korea government (MEST; NRF-2016015679). Support for T. E. Whitledge and D. A.

893   Stockwell was provided by NSF grant #120347.

894

895

896

897

898

899

900

901

902

903

904

905

906

907

908

909

910

911

References

912 Agawin, N.S., Duarte, C.M. and Agustí, S.: Nutrient and temperature control of the contribution
913 of picoplankton to phytoplankton biomass and production. Limnol. Oceanogr., 45(3), pp.591-600,
915 2000.

916 Anderson, L. G. and Kaltin, S.: Carbon fluxes in the Arctic Ocean-potential impact by climate
917 change. Polar Resear., 20(2), 225-232, 2001.

918 Anderson, L. G., Jutterström, S., Kaltin, S., Jones, E.P. and Björk, G.: Variability in river runoff
919 distribution in the Eurasian Basin of the Arctic Ocean. J. Geophys. Res.: Oceans, 109(C1), 2004.

920 Anderson, L. G., Jutterström, S., Hjalmarsson, S., Wåhlström, I. and Semiletov, I.: Out-gassing of
921 CO_2 from Siberian Shelf seas by terrestrial organic matter decomposition. Geophys. Res. Lett., 36,
922 2009.

923 Aksnes, D. L. and Egge, J. K.: A theoretical model for nutrient uptake in phytoplankton. Mar. Ecol.
924 Prog. Ser. , 70, 65–72, 1991.

925 Ardyna, M., Babin, M., Gosselin, M., Devred, E., Rainville, L. and Tremblay, J.É.: Recent Arctic
926 Ocean sea ice loss triggers novel fall phytoplankton blooms. Geophys. Res. Lett., 41(17), 6207-
927 6212, 2014.

928 Arrigo, K. R., van Dijken, G., and Pabi, S.: Impact of a shrinking Arctic ice cover on marine
929 primary production. Geophys. Res. Lett., 35, L19603, 2008.

930 Arrigo, K. R. and van Dijken, G. L.: Secular trends in Arctic Ocean net primary production. J.
931 Geophys. Res., 116, C09011, doi:10.1029/2011JC007151, 2011.

932 Arrigo, K. R., Perovich, D. K., Pickart, R. S., Brown, Z. W., Van Dijken, G. L., Lowry, K. E.,
933 Mills, M. M., Palmer, M. A., Balch, W. M., Bahr, F. and Bates, N. R., Massive phytoplankton
934 blooms under Arctic sea ice. Science, 336(6087), 1408-1408, 2012.

935 Arrigo, K. R. and van Dijken, G. L., Continued increases in Arctic Ocean primary production.
936 Progr. Oceanogr., 136, 60-70, 2015.

937 Bates, N. R., Moran, S. B., Hansell, D. A. and Mathis, J. T.: An increasing CO_2 sink in the Arctic
938 Ocean due to sea-ice loss. Geophys. Res. Lett., 33(23), 2006.

939 Bates, N. R. and Mathis, J. T.: The Arctic Ocean marine carbon cycle: evaluation of air-sea CO_2
940 exchanges, ocean acidification impacts and potential feedbacks. Biogeosciences, 6(11), 2433-2459,
941 2009.

942 Bélanger, S, Babin M, Larouche P.: An empirical ocean color algorithm for estimating the
943 contribution of chromophoric dissolved organic matter to total light absorption in optically
944 complex waters. J. Geophys. Res. 13, C04027. doi:10.1029/ 2007JC004436, 2008.

945 Bélanger, S., Babin, M. and Tremblay, J.E.: Increasing cloudiness in Arctic damps the increase in
946 phytoplankton primary production due to sea ice receding. Biogeosciences, 10(6), p.4087, 2013.

947 Bhavya, P. S., Kumar, S., Gupta, G. V. M., Sudheesh, V., Sudharma, K. V., Varrier, D. S., Dhanya,
948 K. R., Saravanane, N.: Nitrogen uptake dynamics in a tropical eutrophic estuary (Cochin estuary)
949 and adjacent coastal regions during pre-monsoon. Estuar. Coast. http://dx.doi.org/10.1007/s12237-
950 015-9982-y, 2016.

951 Bhavya, P. S., Kumar, S., Gupta, G. V. M., Sudheesh, V.: Carbon uptake rates in the Cochin
952 estuary and adjoining coastal Arabian Sea. Estuar. Coast., 40, 447–456. http://
953 dx.doi.org/10.1007/s12237-016-0147-4, 2017.

954 Boetius, A. and Damm, E.: Benthic oxygen uptake, hydrolytic potentials and microbial biomass at
955 the Arctic continental slope. Deep Sea Res. Pt. I: Oceanogr. Res. Pap., 45(2-3), 239-275, 1998.

956 Bopp, L., Monfray, P., Aumont, O., Dufresne, J. L., Le Treut, H., Madec, G., Terray, L. and Orr,
957 J.C.: Potential impact of climate change on marine export production. Global Biogeochem. Cy.,
958 15(1), 81-99, 2001.

959 Cai, W. J., Chen, L., Chen, B., Gao, Z., Lee, S. H., Chen, J., Pierrot, D., Sullivan, K., Wang, Y.,
960 Hu, X. and Huang, W. J.: Decrease in the CO_2 uptake capacity in an ice-free Arctic Ocean basin.
961 Science, 329(5991), 556-559, 2010.

962 Carmack, E. C., Aagaard, K., Swift, J. H., MacDonald, R. W., McLaughlin, F. A., Jones, E. P.,
963 Perkin, R. G., Smith, J. N., Ellis, K. M. and Killius, L. R.: Changes in temperature and tracer
964 distributions within the Arctic Ocean: Results from the 1994 Arctic Ocean section. Deep Sea Res.
965 Part II: Top. Stud. Oceanogr., 44(8), 1487-1502, 1997.

966 Carmack, E. C. and Macdonald, R. W.: Oceanography of the Canadian Shelf of the Beaufort Sea:
967 a setting for marine life. Arctic, 29-45, 2002.

968 Clasby, R.C., Horner, R. and Alexander, V.: An in situ method for measuring primary productivity
969 of Arctic sea ice algae. J. Fish. Res. Board Can., 30(6), pp.835-838,1973.

970 Codispoti, L. A. and Richards, F. A.: Micronutrient distributions in the East Siberian and Laptev
971 seas during summer 1963. Arctic, 67-83, 1968.

972 Comiso, J. C., Parkinson, C. L., Gersten, R. and Stock, L.: Accelerated decline in the Arctic sea
973 ice cover. Geophys. Res. Lett., 35(1), 2008.

974 Daufresne, M., Lengfellner, K. and Sommer, U.: Global warming benefits the small in aquatic
975 ecosystems. Proc. Nat. Acad. Sci., 106(31), 12788-12793, 2009.

976 Dmitrenko, I. A., Polyakov, I. V., Kirillov, S. A., Timokhov, L. A., Simmons, H. L., Ivanov, V.
977 V. and Walsh, D.: Seasonal variability of Atlantic water on the continental slope of the Laptev Sea
978 during 2002–2004, Earth Planet. Sci. Lett., 244, 735-743, 2006.

Dugdale, R. and Goering, J.: Uptake of new and regenerated forms of nitrogen in primary productivity, Limnol. Oceanogr., 12, 196-206, 1967.

Dugdale, R. C. and Wilkerson, F. P.: The use of ^{15}N to measure nitrogen uptake in eutrophic oceans; experimental considerations. Limnol. Oceanogr., 31(4), 673-689, 1986.

Eastman, R. and Warren, S. G.: Interannual variations of Arctic cloud types in relation to sea ice. J. Clim., 23(15), 4216-4232, 2010.

Eppley, R. W. and Thomas, W. H.: Comparison of half-saturation constants for growth and nitrate uptake of marine phytoplankton. J. Phycol., 5, 375–379, 1969.

Falk-Petersen, S., Hop, H., Budgell, W.P., Hegseth, E.N., Korsnes, R., Løyning, T. B., Ørbæk, J.B., Kawamura, T. and Shirasawa, K.: Physical and ecological processes in the marginal ice zone of the northern Barents Sea during the summer melt period. J. Mar. Sys., 27(1), 131-159, 2000.

Glibert, P.M.: Regional studies of daily, seasonal and size fraction variability in ammonium remineralization. Mari. Biol., 70(2), 209-222, 1982.

Glibert, P.M., Kana, T.M. and Brown, K. From limitation to excess: the consequences of substrate excess and stoichiometry for phytoplankton physiology, trophodynamics and biogeochemistry, and the implications for modeling. J. Mar. Sys. 125, 14-28., 2013.

Gosselin, M., Levasseur, M., Wheeler, P. A., Horner, R. A. and Booth, B. C.: New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep Sea Res. Pt. II Top. Stud. Oceanogr., 44(8), 1623-1644, 1997.

Gradinger R.: Sea-ice algae: major contributors to primary production and algal biomass in the Chukchi and Beaufort seas during May/June 2002. Deep Sea Res. Pt. II, 44(8):1623–1644. doi: 10.1016/j.dsr2.2008.10016, 2009.

Grover, J. P.: Influence of cell shape and size on algal competitive ability. J. Phycol. , 25, 402–405, 1989.

Grover, J. P.: Resource competition in a variable environment: phytoplankton growing according to the variable-internal-stores model. Am. Nat. , 138, 811–835, 1991.

Harrison W. G, Li W. K. W., Smith J. C., Head E. J. H., Longhurst A. R.: Depth profiles of plankton, particulate organic matter and microbial activity in the Eastern Canadian Arctic during summer. Polar Biol. 7.207-224, 1987.

Harrison, W.G. and Cota, G.F.: Primary production in polar waters: relation to nutrient availability. Polar Res., 10(1), pp.87-104, 1991.

Hein, M., Folager Pedersen, M. and Sand-Jensen, K.: Size-dependent nitrogen uptake in micro- and macroalgae. Mar. Ecol. Prog. Ser. , 118, 247–253, 1995.

Hill, V. J., and G. F. Cota.: Spatial patterns of primary production in the Chukchi Sea in the spring and summer of 2002, Deep Sea Res., Pt. II, 52, 3344–3354, 2005.

Hill, V., Ardyna, M., Lee, S. H., and Varela, D. E.: Decadal trends in phytoplankton production in the Pacific Arctic Region from 1950 to 2012, Deep Sea Res. Pt. II, https://doi.org/10.1016/j.dsr2.2016.12.015, 2017.

Hodal, H. and Kristiansen, S.: The importance of small-celled phytoplankton in spring blooms at the marginal ice zone in the northern Barents Sea. Deep Sea Res. Part II Top. Stud. Oceanogr. 55(20), 2176-2185, 2008.

Horner, R. and Schrader, G.C.: Relative contributions of ice algae, phytoplankton, and benthic microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic, pp.485-503, 1982.

Irwin, A.J, Zoe V. F, Oscar M. E. Schofield, Falkowski, P.G.: Scaling-up from nutrient physiology to the size-structure of phytoplankton communities, J. Plank. Res., 28 (5), 459–471, 2006.

Jakobsson, M., and IBCAO Editorial Board Members, Improvement to the International Bathymetric Chart of the Arctic Ocean (IBCAO): Updating the Data Base and the Grid Model, EOS Trans. AGU, 82(46), Fall Meet. Suppl., Abstract no. OS11B-0371, 2001.

Joo, H., Son, S., Park, J.W., Kang, J.J., Jeong, J.Y., Kwon, J.I., Kang, C.K. and Lee, S.H.: Small phytoplankton contribution to the total primary production in the highly productive Ulleung Basin in the East/Japan Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr., 143, pp.54-61, 2017.

Kahru, M., Lee, Z., Mitchell, B. G. and Nevison, C. D.: Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. Biol. Let., 12(11), p.20160223, 2016.

Kirk, J. T. O.: Light and Photosynthesis in the Aquatic Ecosystems, Cambridge Univ. Press, Cambridge, U. K., 1983.

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J. and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. J. Geophys. Res. 114(C7), 2009.

Lee, S. H. and Whitledge, T. E.: Primary and new production in the deep Canada Basin during summer 2002, Polar Biol., 28, 190-197, 2005.

Lee, S. H., Whitledge, T. E. and Kang, S.: Recent carbon and nitrogen uptake rates of phytoplankton in Bering Strait and the Chukchi Sea, Cont. Shelf Res., 27, 2231-2249, 2007.

Lee, S. H., Joo, H. M., Liu, Z., Chen, J. and He, J.: Phytoplankton productivity in newly opened waters of the Western Arctic Ocean, Deep Sea Res. Part II: Top. Stud. Oceanogr., 81, 18-27, 2012.

Lee, S. H., Yun, M. S., Kim, B. K., Joo, H., Kang, S. J., Kang, C. K., and Whitledge, T. E.: Contribution of small phytoplankton to total primary production in the Chukchi Sea, Cont. Shelf Res., 68, 43–50, 2013.

Lee, S. H., Kim, B. K., Lim, Y. J., Joo, H., Kang, J. J., Lee, D., Park, J., Sun-Yong, H. and Lee, S. H., Small phytoplankton contribution to the standing stocks and the total primary production in the Amundsen Sea. Biogeosciences, 14(15), 3705, 2017a.

Lee, S. H., Joo, H. T., Lee, J. H., Lee, J. H., Kang, J. J., Lee, H. W., Lee, D. and Kang, C. K.: Seasonal carbon uptake rates of phytoplankton in the northern East/Japan Sea, Deep-Sea Resear. II, http://dx.doi.org/10/1016/j.dsr2.2017.04.009, 2017b.

Legendre, L., Ackley, S. F., Dieckmann, G. S., Gulliksen, B., Horner, R., Hoshiai, T., Melnikov, I. A., Reeburgh, W. S., Spindler, M. and Sullivan, C.W.: Ecology of sea ice biota. Pol. Biol., 12(3-4), 429-444, 1992.

Levi, B. G.: The decreasing Arctic ice cover, Phys. Today, 53(1), 19–20, doi:10.1063/1.882931, 2000.

Li, W. K., McLaughlin, F. A., Lovejoy, C. and Carmack, E. C.: Smallest algae thrive as the Arctic Ocean freshens, Science, 326, 539, 2009.

Li, J., Glibert, P. M. and Alexander, J. A. Effects of ambient DIN: DIP ratio on the nitrogen uptake of harmful dinoflagellate *Prorocentrum minimum* and *Prorocentrum donghaiense* in turbidistat. Chinese J. Oceanol. Limnol. 29(4), 746-761, 2011.

Martin, J., Tremblay, J. É., Gagnon, J., Tremblay, G., Lapoussière, A., Jose, C., Poulin, M., Gosselin, M., Gratton, Y. and Michel, C.: Prevalence, structure and properties of subsurface chlorophyll maxima in Canadian Arctic waters. Mar. Ecol. Progr. Ser. 412, 69-84, 2010.

Maslowski, W., Marble, D., Walczowski, W., Schauer, U., Clement, J. L. and Semtner, A. J.: On climatological mass, heat, and salt transports through the Barents Sea and Fram Strait from a pan-Arctic coupled ice-ocean model simulation. J. of Geophys. Res.: Oceans. 109(C3), 2004.

McCarthy, J. J., Garside, C. and Nevins, J. L.: Nitrogen dynamics during the Arabian Sea northeast monsoon. Deep Sea Res. Part II Top. Stud. Oceanogr., 46(8), 1623-1664, 1999.

McLaughlin, F.A., Carmack, E.C., Jackson, J.M., Ingram, R.G. and Allen, S.E.: Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993-2008 (Doctoral dissertation, University of British Columbia), 2010.

Niebauer, H. J., Alexander, V. and Henrichs, S.: Physical and biological oceanographic interaction in the spring bloom at the Bering Sea marginal ice edge zone. J. of Geophys. Res.: Oceans, 95(C12), 22229-22241, 1990.

Overland, J. E. and Wang, M.: When will the summer Arctic be nearly sea ice free?. Geophys. Res. Lett., 40(10), 2097-2101, 2013.

Pabi S., van Dijken G., Arrigo K. R.: Primary production in the Arctic Ocean, 1998–2006. J. Geophys. Res. 113:C08005. doi: 10.1029/2007JC004578, 2008.

Parkinson, C. L., Cavalieri, D. J., Gloersen, P., Zwally, J. H., Comiso J. C.: Arctic sea ice extents, areas, and trends, 1978–1996. J. Geophys. Res., 104 (C9), 20837-20856, 1999.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A. and Rahmstorf, S.: Increasing river discharge to the Arctic Ocean. Science, 298(5601), 2171-2173, 2002.

Platt, T., Harrison, W.G., Irwin, B., Horne, E.P. and Gallegos, C.L.: Photosynthesis and photo adaptation of marine phytoplankton in the Arctic. Deep Sea Res. Pt. I: Oceanogr. Res. Pap., 29(10), 1159-1170, 1982.

Quadfasel, D.: Oceanography: The Atlantic heat conveyor slows. Nature, 438 (7068), 565-566, 2005.

Rachold V, Grigoriev MN, Are FE, Solomon S, Reimnitz E, Kassens H, Antonow M.: Coastal erosion vs. riverine sediment discharge in the Arctic shelf seas. Int. J. Earth. Sci. 89, 450–460, 2000.

Redfield, A.C.: The influence of organisms on the composition of seawater. The sea, 2, 26-77, 1963.

Sakshaug, E. and Holm-Hansen, O.: Factors governing pelagic production in polar oceans. In Marine phytoplankton and productivity (pp. 1-18). Springer, Berlin, Heidelberg, 1984.

Sakshaug E.: Primary and Secondary Production in the Arctic Seas. In: Stein R., MacDonald R.W. (eds) The Organic Carbon Cycle in the Arctic Ocean. Springer, Berlin, Heidelberg, 978-3-642-62351-6, 2004.

Semiletov, I., Dudarev, O., Luchin, V., Charkin, A., Shin, K.H. and Tanaka, N.: The East Siberian Sea as a transition zone between Pacific-derived waters and Arctic shelf waters. Geophys. Res. Lett., 32(10), 2005.

Shiklomanov, I.A., Shiklomanov, A.I., Lammers, R.B., Peterson, B.J. and Vorosmarty, C.J.: The dynamics of river water inflow to the Arctic Ocean. In The freshwater budget of the Arctic Ocean (281-296). Springer, Dordrecht, 2000.

Shuter, B. G.: Size dependence of phophorus and nitrogen subsistence quotas in unicellular microrganisms. Limnol. Oceanogr., 23, 1248–1255, 1978.

Slagstad, D. and Wassmann, P.: Climate change and carbon flux in the Barents Sea: 3-D simulations of ice-distribution, primary production and vertical export of particulate organic carbon. Memoirs of National Institute of Polar Research. Special issue, 51, 119-141, 1996.

Slagstad D, Ellingsen I.H, Wassmann P.: Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: an experimental simulation approach. Prog. Oceanogr. 90, 117–131, 2011.

Slawyk, G., Y. Collos, and J.C. Auclair.: The use of the ^{13}C and ^{15}N isotopes for the simultaneous measurement of carbon and nitrogen turnover rates in marine phytoplankton. Limnol. Oceanogr. 22, 925−932, 1977.

Son, S. H., Campbell, J., Dowell, M., Yoo, S. and Noh, J.: Primary production in the Yellow Sea determined by ocean color remote sensing, Mar. Ecol. Prog. Ser., 303, 91-103, 2005.

Steinacher, M., Joos, F., Frolicher, T.L., Bopp, L., Cadule, P., Cocco, V., Doney, S. C., Gehlen, M., Lindsay, K., Moore, J. K. and Schneider, B.: Projected 21st century decrease in marine productivity: a multi-model analysis. Biogeosciences, 7(3), 2010.

Stroeve J, Holland MM, Meier W et al.: Arctic sea ice decline: faster than forecast. Geophys. Res. Lett. 34: L09501, 2008.

Subba Rao, D. V. and Platt, T.: Primary production of Arctic waters. Polar Biol., 3, 191-210, 1984.

Talling, J. F.: The phytoplankton population as a compound photosynthetic system. New Phytol., 56(2), 133-149, 1957.

Thomas, M. K., C. T. Kremer, C. A. Klausmeier, and E. Litchman.: A global pattern of thermal adaptation in marine phytoplankton. Science 338, 1085−1088, 2012.

Tremblay, J. É., Legendre, L., Klein, B., and Therriault, C.: Size-differential uptake of nitrogen and carbon in a marginal sea (Gulf of St. Lawrance, Canada): Significance of diel periodicity and urea uptake. Deep-Sea Res. II, 47, 489-518, 2000.

Tremblay, J.É., Gratton, Y., Carmack, E.C., Payne, C.D. and Price, N.M.: Impact of the large-scale Arctic circulation and the North Water Polynya on nutrient inventories in Baffin Bay. J. Geophys. Res.: Oceans, 107(C8), pp.26-1, 2002.

Tremblay J. E, Gagnon G.: The effects of irradiance and nutrient supply on the productivity of Arctic waters: a perspective on climate change. In: Nihoul JCJ, Kostianoy AG (eds) Influence of climate change on the changing Arctic and sub-Arctic conditions. Proceedings of the NATO advanced research workshop, Liège, May 2008. Springer, Dordrecht, 73–94, 2009.

Vancoppenolle, M., Meiners, K.M., Michel, C., Bopp, L., Brabant, F., Carnat, G., Delille, B., Lannuzel, D., Madec, G., Moreau, S. and Tison, J.L.: Role of sea ice in global biogeochemical cycles: emerging views and challenges. Quaternary science reviews, 79, pp.207-230, 2013.

Vavrus, S. J., Holland, M. M., Jahn, A., Bailey, D. A. and Blazey, B. A.: Twenty-first-century Arctic climate change in CCSM4. J. Clim., 25(8), 2696-2710, 2012.

Vedernikov, V. I., Demidov, A. B. and Sudbin, A. I.: Primary production and chlorophyll in the Kara Sea in September 1993. Okeanologiya, 34(5), 693-703, 1994.

Walsh J. J.: Arctic carbon sinks: present and future. Global. Biogeochem. Cycles 3:393, 1989.

Wassmann, P., Duarte, C. M., Agusti, S., and Sejr, M. K.: Footprints of climate change in the Arctic

1148 marine ecosystem, Glob. Change Biol., 17, 1235–1249, 2011.

1149 Whitledge, T. E., Malloy, S. C., Patton, C. J. and Wirick, C. D.: Automated nutrient analyses in
1150 seawater (No. BNL-51398). Brookhaven National Lab., Upton, NY (USA), 1981.

1151 Yun, M. S., Chung, K. H., Zimmermann, S., Zhao, J., Joo, H. M. and Lee, S. H.: Phytoplankton
1152 productivity and its response to higher light levels in the Canada Basin, Polar Biol., 35, 257-268,
1153 2012.

1154 Yun, M. S., Kim, B. K., Joo, H. T., Yang, E. J., Nishino, S., Chung, K. H., Kang, S. and Lee, S.
1155 H.: Regional productivity of phytoplankton in the Western Arctic Ocean during summer in 2010,
1156 Deep-Sea Res. Part II: Part II Top. Stud. Oceanogr., 120, 61-71, 2015.

1157 Yun, M.S., Whitledge, T.E., Stockwell, D., Son, S.H., Lee, J.H., Park, J.W., Lee, D.B., Park, J.
1158 and Lee, S.H., Primary production in the Chukchi Sea with potential effects of freshwater content.
1159 Biogeosciences, 13(3), pp.737-749, 2016.

1160

1161

1162

1163

1164

1165

1166

1167

1168

1169

1170

1171

1172

1173

1174 Table 1. The physical and chemical properties of sampling locations in the East Siberian Sea and

1175 Laptev Sea, where, station depth, euphotic depth, SST, SSS, and SIC are represented in m, m, ºC,

1176 PSU, and %. The nutrient concentrations ($NO_2^-+NO_3^-$, P, Si, and NH_4^+) are given as the depth-

1177 integrated values in the euphotic zones and its unit is mmol m^{-2}. The DIN:P is the nutrient

1178 stoichiometry calculated from the available nutrient data.

Sector	Stn. Name	Longitude	Latitude	Date	Station depth	Euphotic depth	SST	SSS	SIC	$NO_2^-+NO_3^-$	P	Si	NH_4^+	DIN:P
Laptev Sea	AF005	109.20	78.78	25-Aug-13	283	38	-0.08	31.42	0	142	17.30	184	31.34	10.00
	AF006	118.45	77.59	26-Aug-13	1244	50	0.75	31.36	0	129	16.73	158	18.72	8.81
	AF011	125.80	77.40	27-Aug-13	1543	51	1.62	30.01	0	83.7	23.82	137	2.46	3.62
	AF019	125.74	79.42	28-Aug-13	3196	60	-1.6	32.44	25	132	25.75	144	13.57	5.65
	AF024	125.69	80.72	29-Aug-13	3730	51	-1.48	30.96	45	127	22.34	166	13.74	6.29
	AF036	141.56	80.18	1-Sep-13	1480	54	-1.22	28.29	25	113	7.62	207	11.85	16.39
	AF049	137.77	78.95	5-Sep-13	1552	51	1.57	29.09	0	22.3	9.91	100	3.44	2.60
	AF057	128.83	77.98	5-Sep-13	2325	51	1.49	30.25	0	107	19.96	200	5.60	5.62
	AF061	125.83	78.40	6-Sep-13	2700	51	-0.07	31.39	10	99.4	23.15	190	8.27	4.65
	AF068	107.39	79.76	10-Sep-13	1200	33	-0.35	32.57	0	167	34.20	110	27.64	5.70
	AF071	112.10	82.02	11-Sep-13	3530	43	-1.73	31.86	65	166	20.81	144	15.46	8.72
	AF072	107.48	81.44	12-Sep-13	3349	49	-1.75	32.37	40	132	20.17	89.5	4.32	6.78
	AF080	102.31	80.60	13-Sep-13	315	76	-1.14	32.81	0	107	30.23	38.8	21.68	4.27
East Siberian Sea	AF041	149.38	79.85	2-Sep-13	561	51	-1.57	29.86	60	99.0	16.21	308	19.20	7.30
	AF044	154.98	80.22	3-Sep-13	1904	35	-1.67	30.91	100	88.7	14.48	205	17.43	7.33
Kara Sea	AF091	97.55	82.30	14-Sep-13	2959	38	-1.32	33.30	0	117	25.60	135	17.67	5.27
	AF095	94.79	83.74	15-Sep-13	3668	68	-1.76	32.36	40	121	35.44	165	5.23	3.56
	AF100	90.01	83.75	16-Sep-13	3410	46	-1.49	33.29	0	189	29.02	118	6.62	6.75
	AF116	66.87	81.34	19-Sep-13	530	46	0.47	33.44	0	105	20.52	19.5	22.62	6.22

1179

1180

1181

1182

1183

1184

1185

1186

Table 2. The contribution of small and large phytoplankton towards water column C, NO_3^-, and NH_4^+ uptake rates. The units for column integrated C, and DIN uptake rates are mg C m^{-2}h^{-1} and mg N m^{-2}h^{-1}, respectively. The starred values indicate possibly wrong data due error in uptake rate measurement.

Sector	Stn. Name	Small C uptake rates	Total C uptake rates	Small phytoplankton C uptake contribution (%)	Small NO_3^- uptake rates	Total NO_3^- uptake rates	Small phytoplankton NO_3^- uptake contribution (%)	Small NH_4^+ uptake rates	Total NH_4^+ uptake rates	Small phytoplankton NH_4^+ uptake contribution (%)	Large phytoplankton C uptake contribution (%)	Large phytoplankton NO_3^- uptake contribution (%)	large phytoplankton NH_4^+ uptake contribution (%)
Laptev Sea	AF005	0.86	1.25	68.28	0.06	0.09	72.41	0.94	1.03	90.95	31.72	27.59	9.05
	AF006	4.00	5.78	69.10	0.25	0.42	58.87	1.72	2.18	78.56	30.90	41.13	21.44
	AF011	2.85	4.31	66.02	0.16	0.42	38.47	0.53	0.89	59.83	33.98	61.53	40.17
	AF019	15.96	17.46	88.88	1.02	1.17	86.78	3.73	3.55	*105.1	11.12	13.22	
	AF024	0.69	1.34	51.62	0.08	0.14	56.81	0.31	0.85	36.06	48.38	43.19	63.94
	AF036	2.78	4.27	65.12	0.18	0.20	89.22	0.74	0.84	88.62	34.88	10.78	11.38
	AF049	1.76	4.02	43.86	0.17	0.22	75.57	0.46	0.78	58.44	56.14	24.43	41.56
	AF057	2.68	4.41	60.81	0.30	0.43	69.99	0.29	0.96	30.07	39.19	30.01	69.93
	AF061	1.91	4.38	43.56	0.48	1.53	31.46	0.53	1.91	27.77	56.44	68.54	72.23
	AF068	3.14	5.12	61.35	0.16	0.25	65.10	0.64	0.87	73.87	38.65	34.90	26.13
	AF071	0.54	2.19	24.59	0.22	0.27	79.83	0.33	0.28	*118.2	75.41	20.17	
	AF072	*0.63	*9.30	*6.79	0.27	0.43	63.42	0.27	0.41	65.27	*93.20	36.58	34.73
	AF080	1.68	2.42	69.44	0.33	0.34	*96.66	0.86	1.02	84.58	30.56	*3.34	15.42
East Siberian Sea	AF041	1.24	1.96	63.16	0.06	0.06	*109.6	0.50	0.57	86.92	36.84		13.08
	AF044	1.72	2.18	79.16	0.05	0.04	*129.7	0.11	0.14	75.18	20.84		24.82
Kara Sea	AF091	5.23	9.37	55.79	0.45	0.79	56.87	1.30	1.98	65.80	44.21	43.13	34.20
	AF095	1.73	2.52	68.59	0.28	0.24	*115.7	0.25	0.33	76.13	31.41		23.87
	AF100	1.63	4.85	33.60	0.31	0.56	55.58	0.37	0.82	44.97	66.40	44.42	55.03
	AF116				0.10	0.11	89.23						

Figure 1. Sampling locations in the Kara, Laptev, and East Siberian Seas in the Arctic Ocean. The red straight lines indicate the geographic boundaries to define the seas as per Pabi et al. (2008).
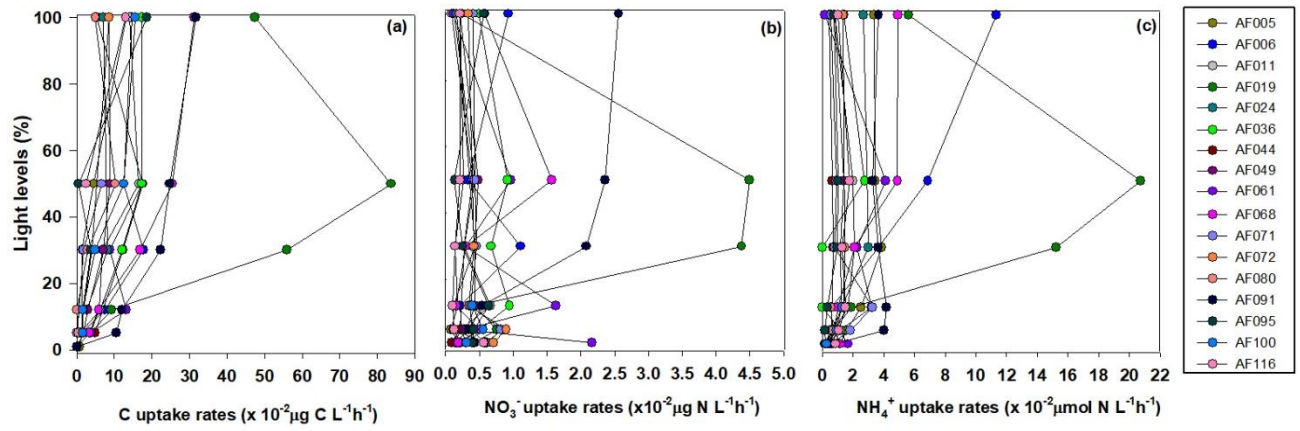
Figure 2. Depth wise small phytoplankton uptake rates of C, NO_3^-, and NH_4^+ in the Kara, Laptev, and East Siberian Sea.
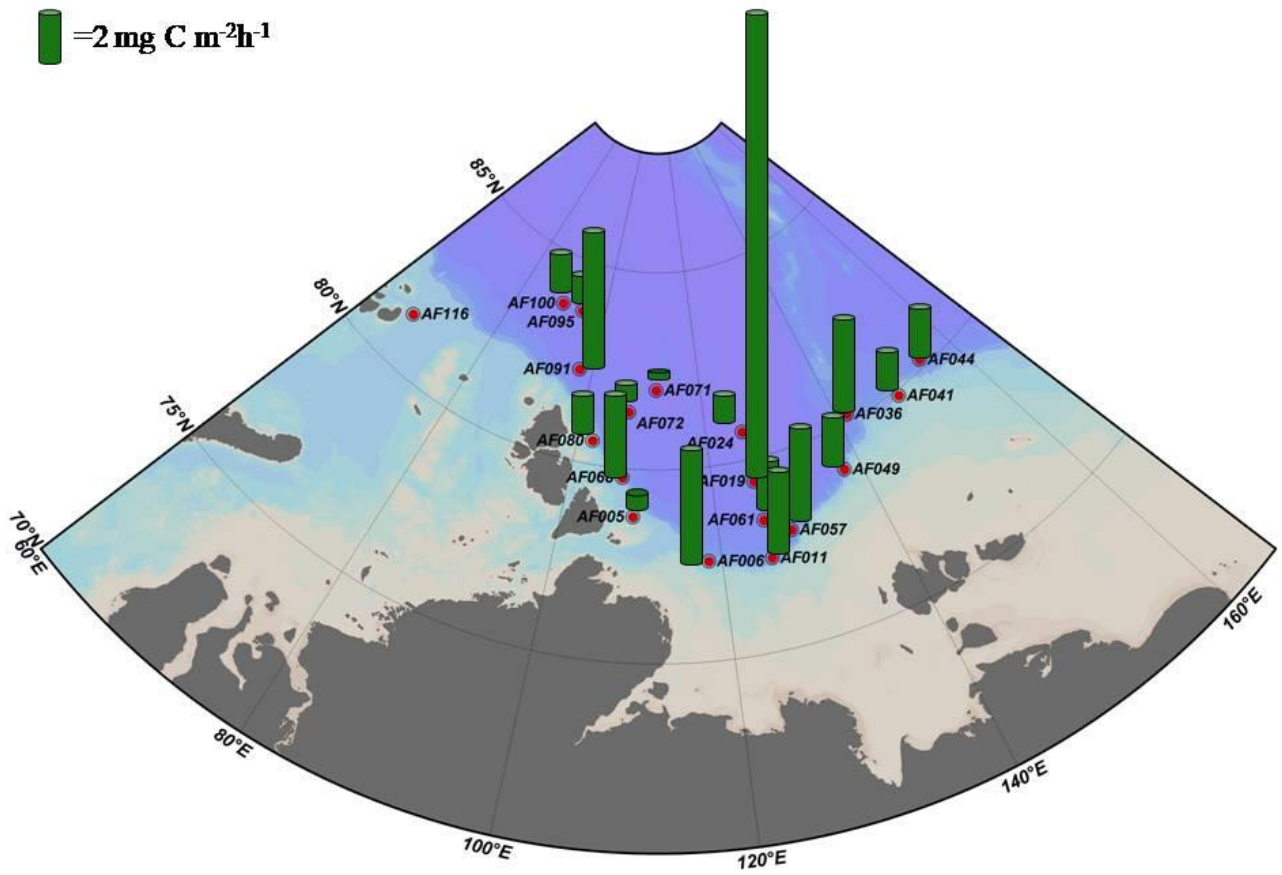
Figure 3. The depth-integrated small phytoplankton C uptake rates in the sampling locations.
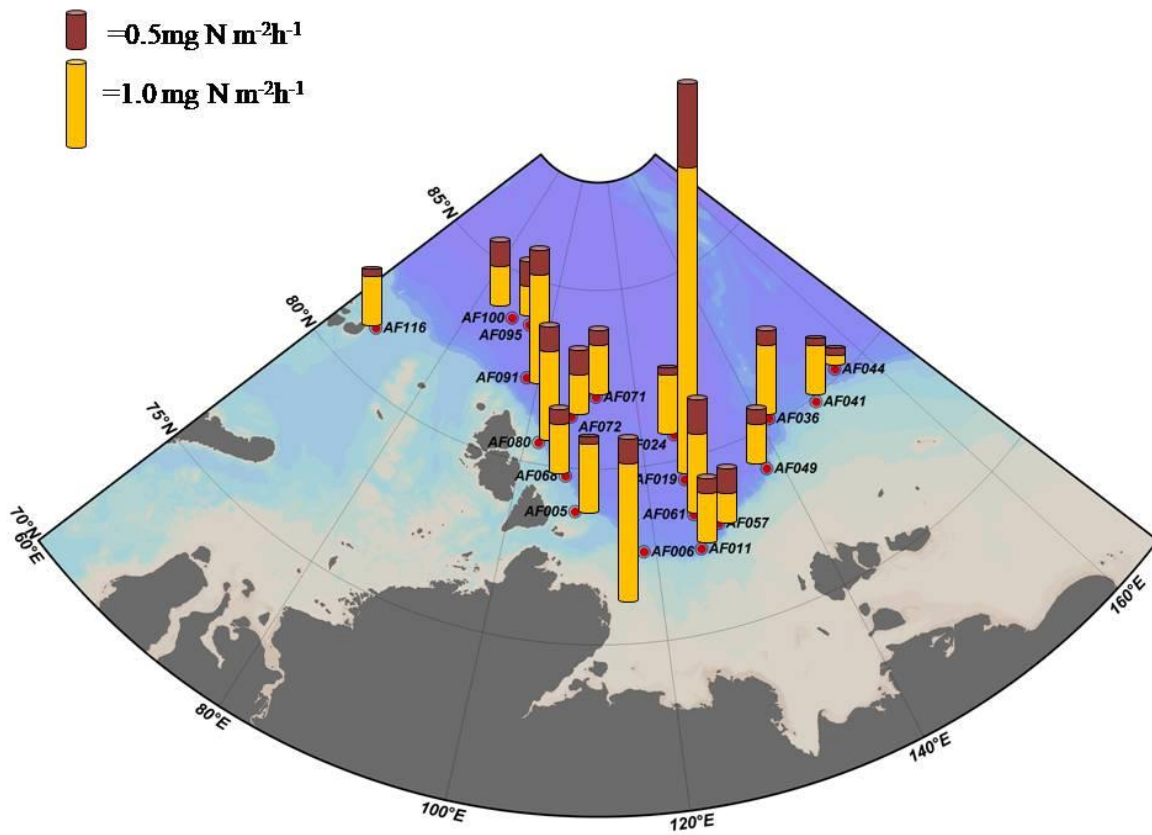
Figure 4. The depth-integrated small phytoplankton NO_3^-, and NH_4^+ uptake rates in the sampling locations. The maroon and yellow cylinders indicate the small phytoplankton NO_3^- and NH_4^+ depth-integrated uptake rates, respectively.
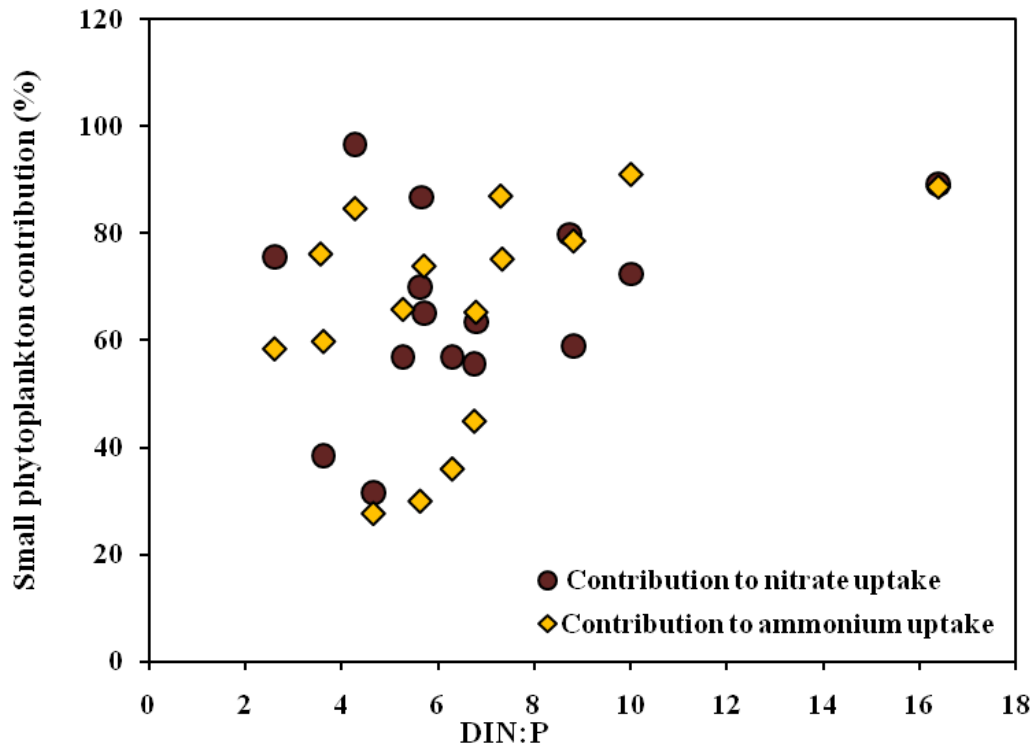
Figure 5. The relationship of contribution of small phytoplankton towards the total NO_3^- and NH_4^+ uptake rates with DIN:P.
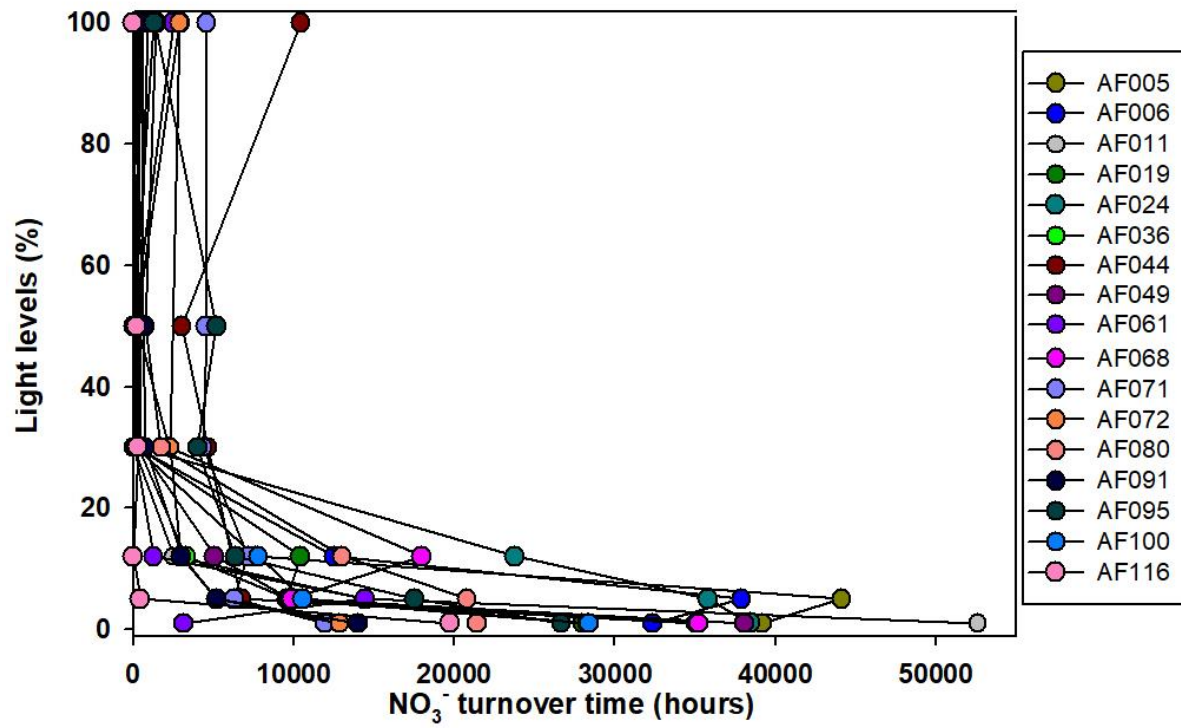
Figure 6. Turnover time for the NO_3^- substrate, when small phytoplankton are the only consumers, in the sampling locations in the Arctic Ocean.
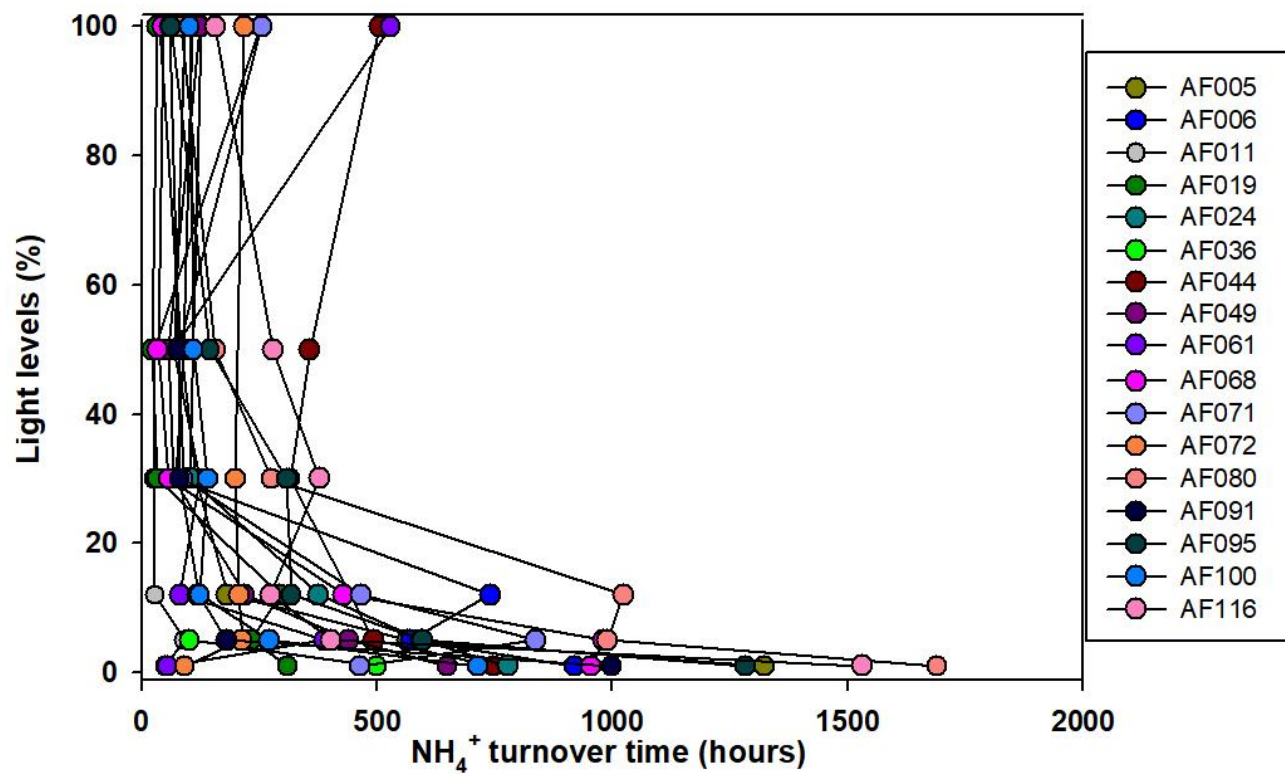
Figure 7. Turnover times for the NH_4^+ substrate, when small phytoplankton are the only consumers, in the sampling locations.
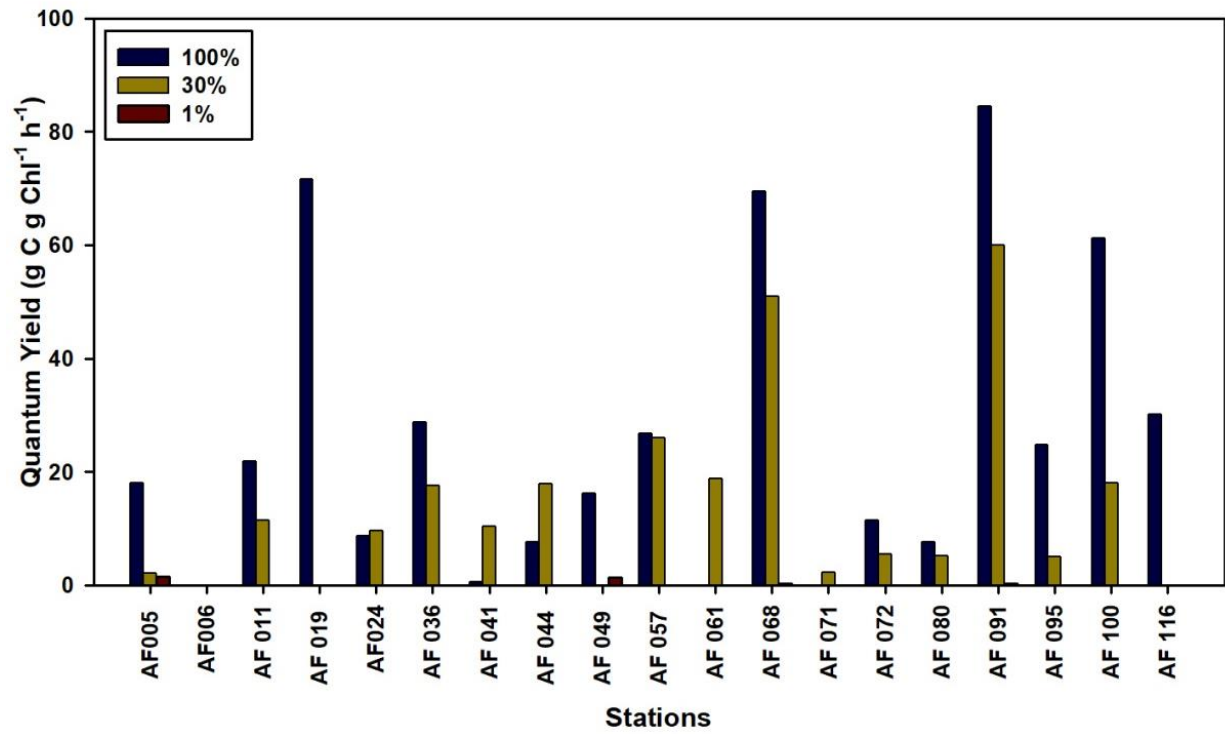
Figure 8. Quantum C Yield of small phytoplankton in the sampling locations.
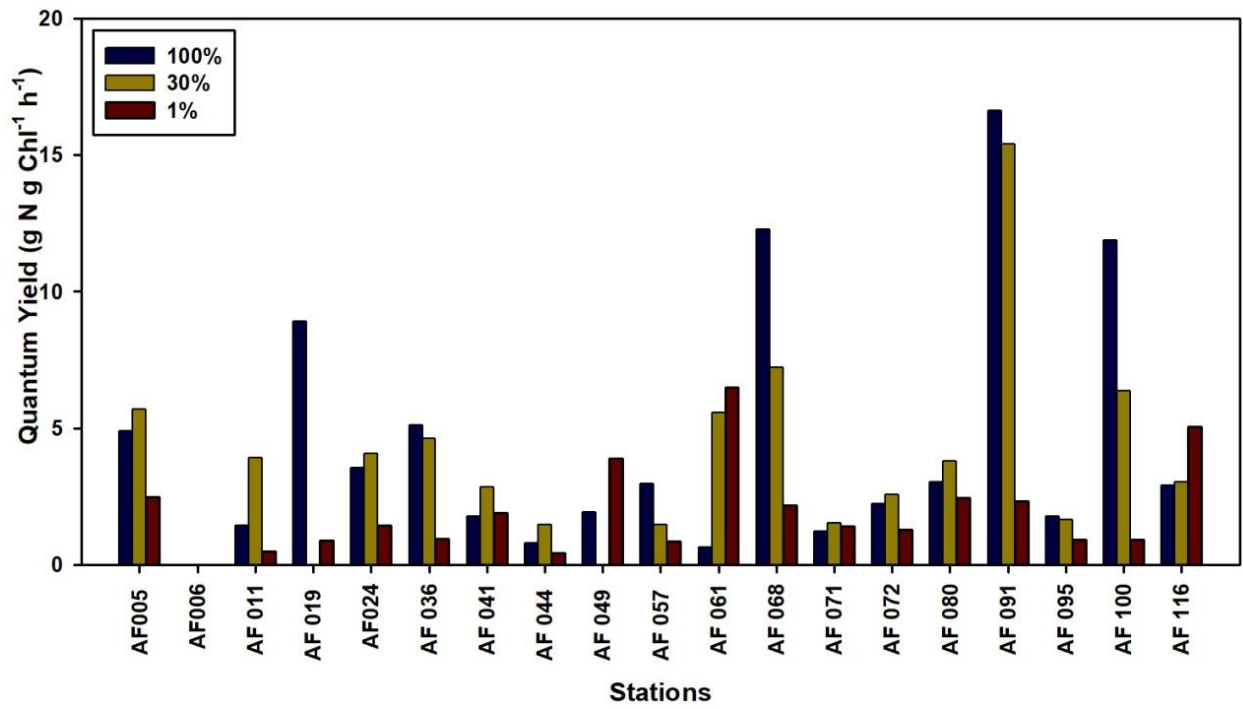
Figure 9. Quantum N yield of small phytoplankton in the sampling locations.