Fluxes of carbon and nutrients to the Iceland Sea surface layer and inferred primary productivity and stoichiometry

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Abstract

This study evaluates long-term mean fluxes of carbon and nutrients to the upper 100 m of the Iceland Sea. The study utilises hydro-chemical data from the Iceland Sea time-series station (68.00 °N, 12.67 °W), for the years between 1993 and 2006. By comparing data of dissolved inorganic carbon (DIC) and nutrients in the surface layer (upper 100 m), and a sub-surface layer (100-200 m), we calculate monthly deficits in the surface, and use these to deduce the long-term mean surface layer fluxes that affect the deficits: vertical mixing, horizontal advection, air-sea exchange, and biological activity. The deficits show a clear seasonality with a minimum in winter, when the mixed layer is at the deepest, and a maximum in early autumn, when biological uptake has removed much of the nutrients. The annual vertical fluxes of

DIC and nitrate amounts to 2.9 ± 0.5 and 0.45 ± 0.09 mol m^{-2} yr^{-1}, respectively, and the annual air-sea uptake of atmospheric CO_2 is 4.4 ± 1.1 mol C m^{-2} yr^{-1}. The biologically driven changes in DIC during the year relates to net community production (NCP), and the net annual NCP corresponds to export production, and is here calculated to 7.3 ± 1.0 mol C m^{-2} yr^{-1}. The typical, median C:N ratio during the period of net community uptake is 9.0, and clearly higher than Redfield, but is varying during the season.

1 Introduction

Increasing our knowledge of the oceanic cycles of carbon and nutrients, and how they are linked, is crucial for improving ocean biogeochemical models and, thus, producing better projections of oceanic response and feedback to a changing climate.

The biological carbon pump, i.e., the biologically driven transport of carbon from the surface waters to the deep ocean, is a pathway that can sequester atmospheric CO_2 on long time scales (Falkowski et al., 1998; Sabine et al., 2004). With the present increase in atmospheric CO_2 (http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html) the strength of the future biological carbon pump is very uncertain, and warrants further investigation (see, e.g., Passow and Carlson, 2012). To be able to reveal changes in the oceans, we need repeated measurements and long-term time-series stations, such as the Hawaii Ocean Time-series (HOT) and the Bermuda Atlantic Time-series Study (BATS) (e.g., Church et al. 2013). In the Nordic Seas, the time-series stations in the Norwegian Sea (Ocean Weather Station Mike) and the Iceland Sea, have greatly increased our knowledge of the carbon cycle in this region (e.g., Skjelvan et al., 2008; Ólafsson et al., 2009). In this paper, we focus on the Iceland Sea, which is the shallowest of the main basins in the Nordic Seas. The Iceland Sea

(Fig. 1) is most often defined as the waters delimited by Greenland in the west, the Denmark Strait and the continental shelf break south of Iceland to the south, by Jan Mayen and the Jan Mayen Fracture Zone to the north and by the Jan Mayen Ridge to the east (Pálsson et al., 2012). The hydrographic properties of the Iceland Sea can generally be described as Arctic Intermediate Water overlying Arctic Deep Water (e.g., Swift and Aagaard, 1981). See Assthorsson et al. (2007) for a more detailed description.

The biological carbon pump in the Nordic Seas has not been studied in great detail, and we need to improve our understanding of the driving processes. Until now there are few estimates of the primary productivity in the relatively cold and low-salinity Arctic waters that dominate the upper water column of the Iceland Sea. Production estimates in this Arctic domain are in the range 75–179 g C m^{-2} yr^{-1}, based on data and remote sensing (Thordardottir, 1984; Zhai et al., 2012).

There are several production terms used in the literature, illustrating somewhat different fluxes. *New production*, as defined by Dugdale and Goering (1967), is the production that results from allochthonous (new) nitrate added to the surface layer by vertical or horizontal advection, or via air-sea exchange. This is different from *total production*, which also includes nitrogen regenerated within the surface layer (see Dugdale and Goering, 1967). *Net community production* (NCP) is defined as net primary production minus community respiration (e.g., Platt et al., 1989). Estimates of NCP have traditionally been based on bottle oxygen incubations (Gaarder and Gran, 1927), but are often based on oxygen budgets (e.g., Falck and Gade, 1999) or seasonal mixed-layer changes in oxygen or inorganic carbon, corrected for the air-sea fluxes (e.g., Körtzinger et al., 2008; Frigstad et al., in prep), or oxygen-to-argon (O_2/Ar) ratios (e.g., Reuer et al., 2007; Quay et al., 2012.). *Export production* is the

excess organic matter produced in the euphotic zone, on top of the production needed to sustain the productive system (Dugdale and Goering, 1967; Eppley and Peterson, 1979). Thus, the export production cannot exceed the rate of added nutrients (i.e. new production), and these fluxes have been assumed to be equivalent on an annual average (Eppley and Peterson, 1979).

An issue under debate over the last few decades, is the universal validity of the so-called Redfield ratio, describing the stoichiometry between carbon and inorganic nutrients in marine plankton, where the average C:N:P ratios are 106:16:1 (Redfield et al., 1963). Observations of deviations from this relationship are numerous (e.g., Takahashi et al., 1993; Anderson and Sarmiento, 1994; Daly et al., 1999; Körtzinger et al., 2001; Koeve, 2006, Tamelander et al., 2013; Frigstad et al., 2014). It is common practise to use the traditional Redfield ratio to convert changes of nutrients into production of organic matter, both in observational and model studies (e.g., Skjelvan et al., 2001; Falck and Anderson, 2005; Skogen et al., 2007), so any significant variability or deviations of these ratios could have a marked impact on estimated primary production.

In this study we use observational data of inorganic nutrients (nitrate, phosphate, and silicate) and inorganic carbon (total dissolved inorganic carbon (DIC) and pCO_2) from the upper layers of the Iceland Sea to evaluate annual fluxes of carbon and nutrients into the surface layer, which we here define as the upper 100 m of the water column. From these fluxes we estimate the long-term mean in primary production in the Iceland Sea, and the related stoichiometric relationships.

2 Data

The study utilises data from the Iceland Sea time series station, located at 68.00 °N, 12.67 °W (Fig. 1). Surface sampling of DIC and pCO_2 started in 1983, and water column sampling for DIC and pCO_2 started in 1991 and 1993, respectively (Ólafsson et al., 2010). Here we include data of inorganic carbon, nutrient and hydrography between 1993 and 2006. For details of analytical methods and data quality, see Olsen (2009), Olafsson and Olsen (2010) and Olafsson et al. (2010). The data are available via the CARINA database (http://cdiac.ornl.gov/oceans/CARINA/Carina inv.html).

Monthly long-term surface wind speed data are from the NCEP/NCAR reanalysis project (Kalnay et al., 1996), provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/.

For the atmospheric CO_2 near Iceland we use Globalview data from Vestmannaeyjar, south of Iceland, ICE_01DO (GLOBALVIEW-CO2, 2012), and the barometric pressure are monthly means of sea level pressure (SLP) obtained from NOWW Fisheries Service, Environmental Research Division (http://www.pfeg.noaa.gov/products/las.html).

3 Methods

This study is based on the climatology (long-term means) of the hydrographical and chemical properties observed in the Iceland Sea. We calculated long-term monthly mean profiles by averaging all data for every month, for the chosen depths (every 10 m in the upper 300 m, every 50 m between 300 and 500 m, and then every 100 m from 500 down to the bottom (1900 m)) and further interpolated to the chosen depth intervals, using piecewise cubic Hermite interpolation in Matlab® (see e.g., Fritsch and Carlson, 1980).

125 The sampling frequency for the different months during the course of the time
126 series sampling is shown in Table 1. The sampling program of the time-series station
127 is largely quarterly (February, May, August, and November), which is clearly seen in
128 Table 1. Four months (January, April, July, and December) have been sampled less
129 than three times, and for these months we use interpolated values.
130 The wintertime mixed layer in the Iceland Sea typically reaches down to 200 m at
131 the end of the winter mixing (Ólafsson, 2003), which is supported by our calculated
132 mean mixed layer depth (MLD) (Fig. 2). We tested several criteria for the MLD,
133 based on either a difference in temperature ($\Delta T = 0.2°C$), or density ($\Delta\sigma_\theta$ = 0.01, 0.03,
134 0.05, and 0.125 kg m^{-3}), all referenced to a near-surface value at 10 m (see, e.g., de
135 Boyer Montégut et al., 2004). The temperature criteria gave unreasonably deep winter
136 convection, with median values of 600-800 m. All density criteria were shallower,
137 however, the 0.125 kg m^{-3} criterion gave a median winter MLD of nearly 400 m,
138 which is not supported by depth profiles of hydrography or biogeochemical
139 parameters (Fig. 3), or by previous estimates (e.g., Ólafsson, 2003). The density
140 difference criteria $\Delta\sigma_\theta$ = 0.05 kg m^{-3} showed the highest agreement with Ólafsson
141 (2003) and was also used by Zhai et al. (2012), which is why we adopted this criteria
142 in the present study. However, the seasonal drawdown in nutrients and DIC (see Fig.
143 3) is largely confined to the upper 100 m. Based on this we define the upper 100 m as
144 the surface layer, and calculate the climatological fluxes in and out of this layer. The
145 approach is described in detail below.
146

147 *3.1 Calculation of deficits*

148 We apply a box-model approach, which was developed for idealised annual
149 plankton cycles (Evans and Parslow, 1985), and has been applied in, e.g., the

Greenland and the Norwegian Seas (Anderson et al., 2000; Skjelvan et al., 2001; Falck and Anderson, 2005). Here we compute deficits (*DEF*) of nutrients and DIC in the surface layer relative to a defined sub-surface layer:

$$DEF_X = \int_{100}^{0} \left([X_{SSL}] - [X_{SL}] \right) \quad (1)$$

where X is the concentration of the constituent of interest (here nutrients and DIC), SSL is the sub-surface layer, and SL is the surface layer. Thus the deficit increases when there is a decrease in carbon or nutrients in the surface layer. While the surface layer is chosen to be the upper 100 m, the sub-surface layer is defined as the layer between 100 and 200 m, for which monthly mean concentrations are calculated and applied in Eq. 1. Applying this on the monthly mean profiles, the deficits are calculated for every 10 m interval in the upper 100 m, relative to the monthly mean concentration in the sub-surface layer, multiplied with 10, and summed up for each month (Anderson et al., 2000).

3.2 Flux calculations

The change in the deficit (ΔDEF^X) of constituent X are explained by the sum of the fluxes into and out of the surface layer; the vertical exchange with the deeper layers (F_{vert}), the horizontal fluxes (F_{hor}), the biological production (F_{bio}), and the air-sea exchange (F_{atm}):

$$\Delta DEF^X = F^X_{vert} + F^X_{hor} + F^X_{bio} + F^X_{atm} \quad (2)$$

Positive fluxes indicate a transport out of the surface layer. Regarding the time-series station as a very thin section the horizontal fluxes will balance, and F_{hor} could then be set to zero. We also assume no atmospheric input of nutrients, and thus F_{atm} is only of importance for the calculations of the DIC fluxes. The uncertainty in the different fluxes is estimated from error propagation of the standard deviations of the different terms in the flux calculations. The uncertainties are discussed in Section 6.

The vertical flux to the surface layer can be calculated from Eq. (3) (Anderson et al., 2000; Skjelvan et al., 2001; Falck and Anderson, 2005):

$$F_{vert}^{X} = \frac{v_{mix}}{H} DEF^{X} \quad (3)$$

where v_{mix} is the vertical entrainment velocity, and H is the thickness of the surface layer. We estimate v_{mix} through changes in the calculated mixed layer depth (following, e.g., Skjelvan et al., 2001), and apply this for the periods with a deepening of the mixed layer, which is the period from September to March seen from the development of the MLD (Fig. 2). During the period from April to August there is a decrease in the MLD, and for this period we apply a background mixing through the base of the mixed layer of 0.1 m d^{-1} (Anderson et al., 2000; Skjelvan et al., 2001), which corresponds to a shallowing of 3.0 m $month^{-1}$. The applied entrainment velocities are shown in Table 1. We here define v_{mix} as negative to get a negative flux when directed into the surface layer.

The flux due to biological activity is given by Eq. 4:

$$F_{bio}^{X} = \Delta DEF^{X} - F_{vert}^{X} - F_{atm}^{X} \quad (4)$$

For the nutrients we assume a negligible atmospheric source, but when calculating the biological production from DIC, F_{bio} needs to be corrected for the air-sea flux (see below). The resulting fluxes are positive as long as the production is greater than the decay of organic matter, as is the case when there is a net biological uptake, removing DIC and nutrients from the surface layer.

The air-sea flux of carbon can be calculated from the difference in partial pressure of CO_2 between seawater and air, the gas transfer velocity k, and the solubility of CO_2 in seawater, K_o:

$$F_{atm} = kK_0 \Delta pCO_2 \quad (5)$$

where

$$\Delta pCO_2 = pCO_2^{sea} - pCO_2^{air} \quad (6)$$

The solubility of CO_2 in the Iceland Sea surface water was calculated after Weiss (1974), using long-term monthly mean values of salinity and temperature in the upper 30 m. For the dependence of wind speed on the transfer velocity k we used the parameterisation of Sweeney et al. (2007) after Wanninkhof (1992):

$$k = 0.27u^2 \sqrt{\frac{660}{Sc}} \quad (7)$$

where u is the long-term surface wind speed (m s^{-1}), and Sc is the Schmidt number. The transfer coefficient was then converted to m $month^{-1}$ by multiplying with (365.25/12)*(24/100).

To calculate the partial pressure in the atmosphere from the molar fractions obtained from GLOBALVIEW we used the formulation:

$$pCO_{2,atm} = XCO_2\left(P_b - P_w\right) \quad (8)$$

where P_b is the barometric pressure (in atmospheres), and P_w is the saturation water vapour pressure calculated from temperature and salinity in the sea surface layer, according to Cooper et al. (1998). Monthly mean seawater pCO_2 values were calculated from observational data over the 13-year time period in the upper 30 m.

4 Results

The deficits of nutrients and DIC in the upper 100 m decrease from January to March (Fig. 4), as a result of the deepened mixed layer depth (Fig. 2). The increase in the deficits after March, related to biological production, continues until a maximum in September, after which the deficits decrease again. There is a small decrease in deficit in phosphate from May to June, which coincides with an almost unchanged deficit in silicate and a slower rate of change of DIC. At the same time the change in the nitrate deficit continues largely as before (Fig. 4). There is a significant uptake of nutrients from winter to late summer (Fig. 3), but on average the system, never gets fully depleted. The calculated fluxes deduced from a change in the deficits, related to vertical mixing, air-sea exchange, and biological production, are presented in the following section and are summarised in Table 2 and Figure 5.

246

247 *4.1 Vertical fluxes*

248 The calculated vertical fluxes add carbon and nutrients to the mixed layer all year
249 around, even though the fluxes during the period of shallow MLD are small. The
250 annual vertical fluxes of DIC and nutrients to the mixed layer was estimated to be 2.9
251 ± 0.5 mol C m^{-2} yr^{-1}, 0.45 ± 0.09 mol N m^{-2} yr^{-1}, 0.026 ± 0.005 mol P m^{-2} yr^{-1}, and
252 0.26 ± 0.06 mol Si m^{-2} yr^{-1}, for DIC, nitrate, phosphate, and silicate, respectively. The
253 flux of DIC equals 35 g C m^{-2} yr^{-1}. The presented uncertainties are calculated from
254 error propagation of the terms in equation 3. (See details in Section 6.2).
255

256 *4.2 Air-sea flux of CO_2*

257 The air-sea flux is directed into the surface layer all year around, as the region is
258 permanently undersaturated with respect to atmospheric CO_2 (Fig. 5). The calculated
259 annual flux was 4.4 ± 1.1 mol C m^{-2} yr^{-1}, which is consistent with the estimate of
260 Ólafsson et al. (2009) of 4.5 mol C m^{-2} yr^{-1}. When converted, the calculated flux into
261 the Iceland Sea is 53 g C m^{-2} yr^{-1}.
262

263 *4.3 Biological production*

264 The biologically related fluxes of carbon and nutrients all show a two-peak
265 seasonality, with the first maximum in April-May, and a second, larger peak in
266 September. Phosphate shows a slightly different evolution, with no flux in June, and a
267 broader peak in late summer, with a small maximum in August. The nutrients also
268 show a negative flux in October, when there is still a net uptake of carbon.

269 The change in the deficit (ΔDEF) equals zero over the course of the year, and
270 hence there is a balance between the calculated fluxes (Eq. 2). For the nutrients, with
271 the assumption of negligible horizontal and air-sea fluxes, there is a balance between
272 the net vertical fluxes and the net biological fluxes, and the latter amounts to 0.45 ±
273 0.14 mol N m^{-2} yr^{-1}, 0.026 ± 0.010 mol P m^{-2} yr^{-1}, and 0.26 ± 0.16 mol Si m^{-2} yr^{-1},
274 respectively (Table 2). Following the definition of new production (Dugdale and
275 Goering, 1967), and our assumptions of negligible horizontal and air-sea flux of
276 nitrate, the addition of nitrate from vertical mixing must equal new production. In the
277 Iceland Sea this amounts to 0.45 ± 0.09 mol N m^{-2} yr^{-1}.
278 The biologically driven change in DIC, corrected for vertical flux and air-sea
279 exchange, corresponds to NCP, with positive numbers illustrating net autotrophy, and
280 negative values net heterotrophy. There is a very small or negative NCP in the first
281 part of the year, but from March to October there is a net autotrophic production (Fig.
282 5). There is also a small positive NCP in December, but this could be due to the fact
283 that the values have been interpolated because there is less data available in December
284 and January. This will not be discussed further.
285 The net annual NCP corresponds to the export production, when assuming steady
286 state. In the Iceland Sea this sums up to 7.3 ± 1.0 mol C m^{-2} yr^{-1}, or 88 ± 12 g C m^{-2}
287 yr^{-1}.
288 The seasonal drawdown of nitrate, corresponding to the period of net community
289 uptake (i.e. increasing deficit; April to September; see Fig. 4), relates to the total
290 production. This period shows positive biological fluxes, and the sum of these
291 amounts to 0.72 ± 0.10 mol N m^{-2} yr^{-1}. The difference between the new and total
292 production (0.27 ± 0.15 mol N m^{-2} yr^{-1}) gives the regenerated production, which
293 represents 37% of the total production. Then we get an *f*-ratio (i.e. the ratio between

294 new and total production) of 0.63 in the Arctic domain of the Iceland Sea. Performing
295 the same calculations for phosphate and silicate gives a total production of 0.036 ±
296 0.006 mol P m^{-2} yr^{-1} and 0.40 ± 0.07 mol Si m^{-2} yr^{-1}.
297

298 *4.4 Stoichiometry of the calculated fluxes*

299 An evaluation of the stoichiometric relationships between carbon and nutrients
300 show varying values during the year, as well as for the different fluxes (Table 3).
301 Evaluating the stoichiometry for the biological production is not straightforward
302 since the flux of carbon and nitrate do not show the same direction for all months. The
303 change in deficits of DIC and nitrate (Fig. 4), however, both show a net uptake from
304 April to September, so we will use this period to evaluate the biologically related
305 stoichiometry. The C:N ratios of the monthly biological production (Fig. 7), during
306 the period of seasonal drawdown of DIC and nitrate, differ between the early and the
307 late part of the season, with C:N ratios of 8.8-8.9 in April and May, and 9.1-9.8
308 between July and September, while the value in June is 7.4.
309

310 **5 Discussion**

311 *5.1 Primary production in the central Iceland Sea*

312 The main aim of this study is to investigate primary production and related
313 stoichiometry in the central Iceland Sea. This domain is dominated by Arctic waters,
314 and is the least productive of the waters around Iceland (e.g., Gudmundsson, 1998;
315 Assthorsson et al., 2007). However, it could be representative of the whole Arctic
316 domain in the Nordic Seas, with similar hydro-chemical properties.

How realistic is our estimated annual net production (NCP) of 88 ± 12 g C m^{-2} yr^{-1} in the Iceland Sea? Gudfinnsson (2012) found, from his data of daily productivity, an average annual phytoplankton productivity of 65 g C m^{-2} yr^{-1}, and Thordardottir (1984) presented an average annual primary production (1958–1982) in the Arctic domain, in the vicinity of the time series station, of 75 g C m^{-2} yr^{-1}, based on measured ^{14}C uptake at light saturation. A modelling study (Skogen et al., 2007), suggests a mean annual production in the Iceland Sea at 70 g C m^{-2} yr^{-1}, with an *f*-ratio of ~0.7. These estimates show a large agreement with the estimates in our study, giving more trust in our results, and the approach. The uncertainty in our presented fluxes, and the approach in general, are discussed in Section 6.

From remote sensing data, Zhai et al. (2012) gave a production estimate in the Arctic domain of 179 ± 36 g C m^{-2} yr^{-1}. This is more than twice as high as the estimates based on in situ data. This has also been seen in other comparisons between production estimates based on in situ and remote sensing data (see, e.g., Richardson et al., 2005; Körtzinger et al., 2008; Frigstad et al., in prep).

The negative nutrient flux in October, when there is still a net uptake of carbon (Fig. 5), is similar to what have been observed in the Norwegian Sea (Falck and Anderson, 2005), which were explained largely by a build-up of dissolved organic matter (DOM), which is relatively low in nutrients. We will discuss this further below, in relation to the stoichiometry of the production.

5.2 Variable stoichiometry

The evaluation of the C:N ratios during seasonal drawdown (April to September) of DIC and nitrate (Fig. 6) showed a clear deviation from the Redfield C:N ratio of 6.6, except in June, when the production was lower. The consumption of carbon

342 relative to nitrate in excess of Redfield, a phenomena termed “carbon
343 overconsumption” (Toggweiler, 1993), was higher during the late summer production
344 (C:N ratio >9) compared to the early production peak (C:N ratio <9). Similar
345 increases in carbon overconsumption during the later part of the productive season
346 have been described in several studies from different ocean regions, and have been
347 explained by the build up of low-nitrogen DOM (e.g., Toggweiler, 1993; Williams,
348 1995; Kähler and Koeve, 2001; Körtzinger et al., 2001). Without any data of DOM in
349 the central Iceland Sea we cannot find direct evidence supporting this mechanism in
350 our study, but the similarity to the Atlantic-dominated Norwegian Sea (Falck and
351 Anderson, 2005) suggest that this may be a general feature also in the Nordic Seas.
352 This should be evaluated further in the future. Nonetheless, different mechanisms
353 seem to affect the flux of carbon and nitrogen during the season, as shown for
354 different regions (e.g., Banse, 1994; Kähler and Koeve, 2001; Frigstad et al., 2011).
355 If we compare the total new production and NCP during the year, from the values
356 in Table 2, we get a net C:N ratio of 16.2. This means that, if we would convert the
357 computed new production into export production, using the ratios of Redfield (6.6), or
358 Takahashi et al. (7.3), we would underestimate the export production by 55–60%,
359 assuming our estimated export production is reasonable. This confirms the findings
360 of, Sambrotto et al. (1993), who found that the actual carbon production exceeds any
361 estimate based on nitrogen consumption, converted by the Redfield C:N ratio, by 36–
362 81%.
363 This illustrates the problem in converting new production into NCP, or export
364 production, using constant stoichiometric ratios. As discussed by Laws (1991) these
365 terms may not be related, and would assume that nitrate and carbon are assimilated by
366 autotrophs during new production, in the same ratio as carbon and nitrate are recycled

by heterotrophs. Furthermore, C:N ratios have been observed to differ both between seasons (e.g., Körtzinger et al., 2001; Frigstad et al. 2011) and between regions (e.g., Koeve, 2006; Tamelander et al., 2013; Frigstad et al., 2014), with values as high as ~15.

An evaluation of the relationship between DIC and nitrate in the surface water using the time-series data (not shown) gives a high agreement with the estimated stoichiometry in the region by Takahashi et al. (1993). However, this value represents the relationship between measured properties in the surface waters over the year, which includes the net effect of air-sea exchange, biological activities, and mixing. Due to this, Banse (1994) cautioned against using observed in-situ DIC:nitrate relationships to make statements about elemental ratios during biological production, and respiration, and recommended smaller closed, controllable systems to find mechanistic explanations of uptake ratios in the surface layer.

5.3 Comparison to production estimates for other parts of the Nordic Seas

How representative of the Nordic Seas are our estimated production terms in the Iceland Sea? The average NCP in the Nordic Seas, based on an oxygen budget, have been estimated to ~36 g C m^{-2} yr^{-1} (Falck and Gade, 1999). This is roughly half of the annual NCP we find in the central Iceland Sea. However, to evaluate regional differences we compare with estimates for the different basins in the area.

For the Greenland Sea, Richardson et al. (2005) estimated the annual primary production to 81 g C m^{-2} yr^{-1}, or 70 g C m^{-2} yr^{-1}, if excluding observations within the ice or at the ice edge. Anderson et al. (2000) estimated the annual new production, in the upper 150 m, of 34 g C m^{-2} yr^{-1}, based on a box model similar to ours, and nitrate data (using a C:N ratio of 7.5). With an *f*-ratio of 0.56 (Smith, 1993) this corresponds

392 to a total production of 61 g C m^{-2} yr^{-1} (Richardson et al., 2005). The likely range of
393 annual primary production in the Greenland Sea is in the range 60–100 m^{-2} yr^{-1}
394 (Richardson et al., 2005), which is in agreement with the range of estimates for the
395 Iceland Sea.
396 In the Norwegian Sea, the primary production has been estimated to 80 g C m^{-2} yr^{-1}
397 (Rey, 2004) and that the new production is 60% of that. It has also been pointed out
398 that where zooplankton grazing is high as in the Norwegian Sea new production may
399 be underestimated (Bathmann et al., 1990) and could be as high as 80%. Results from
400 a modelling study (Skogen et al., 2007), suggests a mean annual production in the
401 Norwegian Sea at 65 g C m^{-2} yr^{-1}, with an *f*-ratio of ~0.75.
402 Falck and Anderson (2005) used a box model approach similar to the present
403 study, and for the Norwegian Sea, they assumed the export production to correspond
404 to the vertical flux of nutrients to the surface layer (upper 100 m), which equalled
405 0.23 N m^{-2} yr^{-1}, or 18 g C m^{-2} yr^{-1}; when using the traditional Redfield C:N ratio (6.6).
406 Their new production estimate amounted to 0.51 mol N m^{-2} yr^{-1}, or 41 g C m^{-2} yr^{-1},
407 using the same ratio. If equating their vertical flux of nitrate with new production, and
408 their total production with the sum of all positive biological fluxes during the year, we
409 get an *f*-ratio of 0.43. This is clearly lower than the earlier estimates mentioned above
410 (Rey, 2004; Skogen et al., 2007).
411 Earlier estimates of new production in the Norwegian Sea (70°N, 0°E) are in the
412 range 21-29 g C m^{-2} yr^{-1} (Bodungen et al., 1995). These values agree with estimates of
413 NCP, based on oxygen fluxes in the Norwegian Sea, of ~24-32 g C m^{-2} yr^{-1} (Skjelvan
414 et al., 2001). The new production estimate is in reasonable agreement with what we
415 estimate for the Iceland Sea, but it is clear that previous NCP estimates based on
416 oxygen budgets are significantly lower than what we get in the Iceland Sea. This

417 could partly be due to the oxygen-to-carbon conversion applied, mostly based on the
418 traditional Redfield ratio, but the only way to unravel real or artificial differences is to
419 analyse the whole region with the same method. This should be pursued in the near
420 future to investigate regional differences, but also to evaluate trends and changes in
421 the system. Nevertheless, the range of methods and approaches, both based on
422 observations and models, and different assumptions, including ours, still seems to
423 reach some consensus of annual primary production in the Nordic Seas of ~60-100 g
424 C m^{-2} yr^{-1}. More work is needed to evaluate regional similarities and differences in
425 stoichiometry and any temporal trends in primary production. This will aid
426 understanding of the variability drivers in biological production, both natural and
427 anthropogenic, and how the increasing levels of atmospheric CO_2 will affect the
428 biological carbon pump.
429

430 **6 Uncertainties**

431 One obvious source of error is the fact that our approach only makes long-term
432 averages for all months, so any trends in the observed properties will cause some
433 uncertainty in the resulting values. With this in mind we proceed to evaluate the
434 uncertainty of the approach and the individual fluxes.
435

436 *6.1 Deficit calculations*

437 The uncertainties in the deficit calculations are related to the interannual variability in
438 the observed concentrations in the surface layer and in the sub-surface reference
439 concentrations, and the uncertainties arising from the averaging procedures of the
440 monthly profiles. The uncertainty in the monthly surface layer concentrations (seen

441 from the average monthly standard deviation) is largest for silicate (values up to 40–
442 50%), but for nitrate and phosphate there is a maximum in late summer/early autumn,
443 when the concentrations are lowest by 20–30%. Due to the high concentrations of
444 DIC the uncertainty in these numbers is insignificant. If we propagate the
445 uncertainties in the surface concentrations and the reference concentrations and use
446 this as the overall uncertainty in the monthly deficits we get the values depicted in
447 Figure 4, which are quite substantial for some of the months, with a relative error of
448 up to 60-75% at or just after the early peak in production, but lower (10–40%) during
449 the later part of the year. The uncertainty in the values from the first part of the year,
450 during the period of deepened mixed layer, is rather low in an absolute sense,
451 compared to later in the year, but due to the low deficits in this period the relative
452 errors get very large (see Fig. 4).
453 There is a potential error in assessing the production, and related terms, in the
454 upper 100 m, when the MLD apparently reaches deeper in winter. However, the
455 vertical distribution of nutrients and DIC do show a homogeneous upper 100 m in
456 winter, followed by a gradient down to stable concentration at depths below ~300 m.
457 Profiles of salinity show the same feature (Fig. 3). Deficits were also calculated for
458 the upper 200 m (referenced to the monthly means between 100 and 200 m), and the
459 upper 300 m (referenced to the monthly means between 300 and 400 m). The
460 resulting deficits of carbon and nutrients showed an increasing degree of decoupling
461 with increasing depth of the surface layer, as shown in Figure 7. The C:N ratio during
462 the period of net biological uptake also varies considerably more with thicker surface
463 layer (not shown) compared to the upper 100 m. With a surface layer down to 200 m
464 the C:N uptake ratio is 20 during the spring peak, below 4 in June, and show values
465 between 13 and 19 from July to September. A surface layer of 300 m gives C:N

466 uptake ratios of 10 during the spring peak, followed by negative values during
467 summer, and a value of 4 in September. This suggests that processes other than
468 biological assimilation contributed much more to the distribution of nutrients and
469 carbon at these depths Since we mainly want to evaluate the fluxes of importance for
470 the production, and these seem to be confined to the upper 100 m, we argue that the
471 applied method best captures the biological production with the relatively shallow
472 surface layer we use. This may also be connected to the different water masses
473 present in the Iceland Sea, so it is important to evaluate different surface layer
474 thickness in different regions.
475

476 *6.2 Vertical flux*

477 The uncertainty in the vertical fluxes could be significant. With the assumption that
478 the air-sea fluxes, as well as the horizontal fluxes of nutrients could be neglected, the
479 increase in nutrient concentration during periods of deepened mixed layer depths
480 should equal the vertical fluxes. Since we estimate the vertical entrainment velocity
481 from the observed changes in MLD, there is both an uncertainty related to the chosen
482 method to calculate MLD, and the variability in the monthly MLD during the time
483 series. The variability-driven uncertainty in the mean monthly MLD is on average
484 ~30% (Fig. 2). The calculated uncertainty in the vertical fluxes of DIC, and nutrients
485 are all in the range 17–22% (see Table 2).
486

487 *6.3 Air-sea exchange*

488 From the propagation of the errors due to spread in mean pCO_2 values for atmosphere
489 and sea surface, and putting this error estimate in the flux calculation for each month,

490 we get an annual uncertainty of 1.1 mol C m^{-2}, which is 25% of the estimated annual
491 flux. This agrees with previous findings from the North Atlantic and the Nordic Seas
492 (Körtzinger et al., 2001; Olsen et al., 2003). Körtzinger et al. (2008) have estimated a
493 maximum error in calculated CO_2 fluxes of 40%.
494

495 *6.4 Biological production*

496 Since the biological production is calculated as the residual of all other terms (Eq. 4)
497 it also carries the uncertainty of each of these terms. Some of the uncertainty could be
498 connected to interannual variability in the timing of the peak in the productive events,
499 something that should be evaluated further in later studies. To estimate the uncertainty
500 in the ΔDEF term we use the relative error in the calculated deficits, and multiply
501 these with the ΔDEF values for each month, for each constituent. The relative error in
502 the deficit for the months with very low values (February–March) is unrealistically
503 large. For these months we instead use the uncertainty in MLD as the minimum error.
504 For February this is ~50%, and for March ~30%. The total estimated errors in the
505 biologically related fluxes are in the range 31-61% for the nutrients (highest for
506 silicate), but only 14% for carbon (Table 2).
507

508 **7 Conclusions**

509 The computed monthly fluxes of dissolved inorganic carbon, nitrate, phosphate
510 and silicate in the Iceland Sea show similarities in the seasonality, but also a
511 decoupling during the year, illustrating different mechanisms effecting the uptake and
512 remineralisation of the different constituents. We estimate an Iceland Sea new
513 production of 0.45 ± 0.09 mol N m^{-2} yr^{-1}, based on nitrate added to the surface layer

514 via vertical mixing, and an annual net community production (NCP) of 7.3 ± 1.0 mol
515 C m^{-2} yr^{-1} (or 88 ± 12 g C m^{-2} yr^{-1}). The presented NCP shows a high agreement with
516 earlier estimates of primary production in the Iceland Sea, and to other parts of the
517 Nordic Seas. The estimated C:N ratios during net biological uptake are in the range
518 7.4-9.8, and thus indicate that a conversion of the nitrate-based new production to
519 carbon using traditional Redfield C:N would markedly underestimate the primary
520 production in the Iceland Sea.
521
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526
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718

719 **Tables**

720

721 **Table 1.** Monthly computed median mixed layer depths (MLD) and entrainment

722 velocities (v_{mix}). These are used when calculating the vertical fluxes. The values in

723 italic are interpolated from surrounding monthly data. See text for details.

Month	MLD Median (m)	v_{mix}[a] (m month^{-1})	Number of sampled months[b]
1	*118*	*–29*	2
2	147	–29	16
3	168	–21	3
4	*116*	–3	1
5	65	–3	14
6	30	–3	8
7	*25*	–3	1
8	21	–3	16
9	32	–11	4
10	37	–5	4
11	59	–22	14
12	*89*	*–30*	2

724 [a] v_{mix} is defined as negative to get a negative flux into the surface layer.

725 [b]This is the number of sampled months in the data set. For months sampled less than

726 three times, interpolated numbers have been used.

727

728 **Table 2.** Summary of annual fluxes (mol m^{-2} yr^{-1}) of carbon, nitrate, phosphate, and
729 silicate to the surface layer (upper 100 m) of the Iceland Sea; vertical flux (F_{vert}), air-
730 sea flux (F_{atm}), and biological production (F_{bio}). Negative values indicate a flux into
731 the surface layer. The horizontal fluxes are assumed to balance over the year and were
732 set to zero.

	F_{vert} (mol m^{-2} yr^{-1})	F_{atm} (mol m^{-2} yr^{-1})	F_{bio} (mol m^{-2} yr^{-1})
Carbon	−2.9 ± 0.5	−4.4 ± 1.1	7.3 ± 1.0[a]
Nitrate	−0.45 ± 0.09	–	0.45 ± 0.14[b]
Phosphate	−0.026 ± 0.005	–	0.026 ± 0.010
Silicate	−0.26 ± 0.06	–	0.26 ± 0.16

733 [a]Corresponds to NCP

734 [b]Corresponds to new production

735

736 **Table 3.** Stoichiometric (median) ratios of computed monthly vertical fluxes and of
737 biological production during the period of seasonal drawdown (net community
738 uptake).

	Vertical flux[a] (Annual)	Net uptake[a] (Apr–Sep)
N:P	18.4	18.2 [b]
C:N	6.20	9.00
C:P	112	159 [b]
C:Si	11.1	25.9
N:Si	1.67	2.72
Si:P	10.5	13.3 [b]

739 [a]We use the median of the monthly values since some months show large deviations.
740 [b]Since the biologically related flux of phosphate is zero in June these numbers are
741 only based on Apr–May, and July–Sept.
742
743
744

745 **Figure captions**

746 Figure 1. Map of the Nordic Seas region. The red filled circle marks the position of
747 the time-series station.

748

Figure 2. Calculated mixed layer depth (MLD) at the Iceland Sea time-series station, using the density difference criteria of $\Delta\sigma_\theta$ 0.05 kg m^{-3}. The grey dots show the MLD for each year, and the line is the median of the values for each month, and the error bars show the standard deviation (SD). The values for the months without shown data are interpolated.

749

Figure 3. Mean monthly concentration profiles (upper 500 m) in the Iceland Sea, of salinity (upper left), potential temperature (upper right), nitrate (middle left), phosphate (middle right), silicate (lower left), and DIC (lower right). The black profiles indicate months with an increase in MLD (compared to previous month) and the red profiles depict months with a decreased or very shallow (<40 m) MLD (see Fig. 2).

750

Figure 4. Calculated monthly-mean deficits of nitrate, phosphate, silicate, and carbon, in the upper 100 m in the Iceland Sea. For the calculations we used mean monthly values for the 100-200 m depth range as reference. The error bars show the propagated error (uncertainty) from the standard deviation of the respective reference concentrations and the average monthly standard deviation in the surface layer. As for the MLD calculations, for the months sampled less than three times in the time series we have used interpolated values. See text for details.

751

Figure 5. Calculated seasonal fluxes to the upper 100 m in the Iceland Sea, for nitrate, phosphate, silicate and DIC. All fluxes are in mol m^{-2} $month^{-1}$. The figures show the vertical flux (F_{vert}; solid black line), the biological production (F_{bio}; green solid line), and the air-sea flux of CO_2 (F_{atm}; red dashed line for carbon). The error bars show the propagated errors (see Section 6). Note that the scale on the y-axis is different for all constituents.

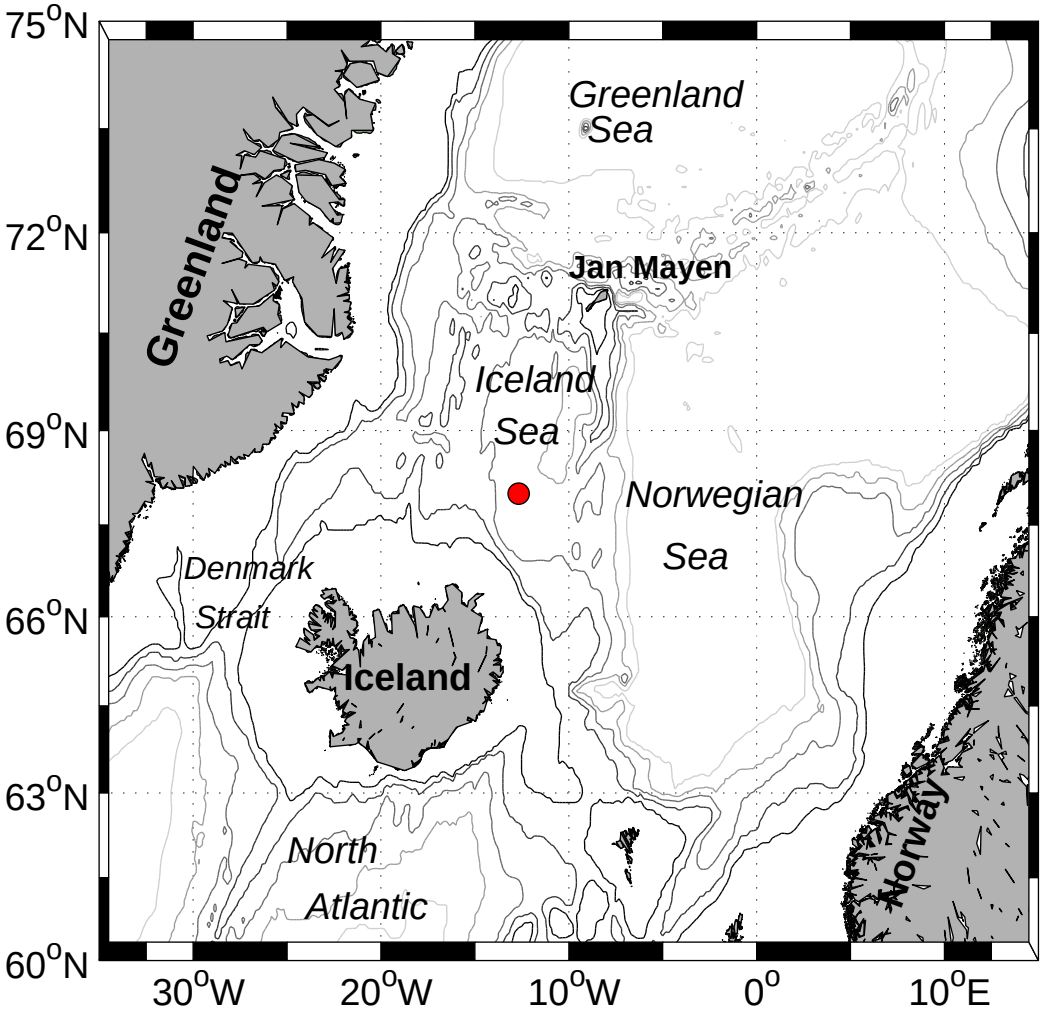
752

753 Figure 6. Average monthly C:N ratios for biological production (see Fig. 5) during the
754 period of seasonal drawdown (April–September) of DIC and nitrate in the Iceland
755 Sea. Then red line show the Redfield C:N ratio of 6.6.

756

757 Figure 7. Comparison of calculated monthly-mean deficits of DIC and nitrate in the
758 Iceland Sea, for different thickness of the surface layer (SL). The nitrate deficits are
759 multiplied with the Redfield C:N ratio of 6.6.

760


75°N
72°N
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60°N
30°W
20°W
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Greenland
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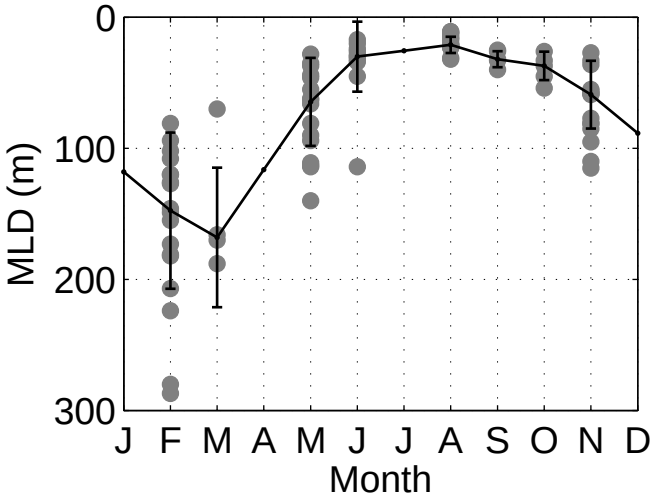
Jan Mayen
Iceland Sea
Norwegian Sea
Denmark Strait
Iceland
North Atlantic
Norway


0
100
200
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MLD (m)
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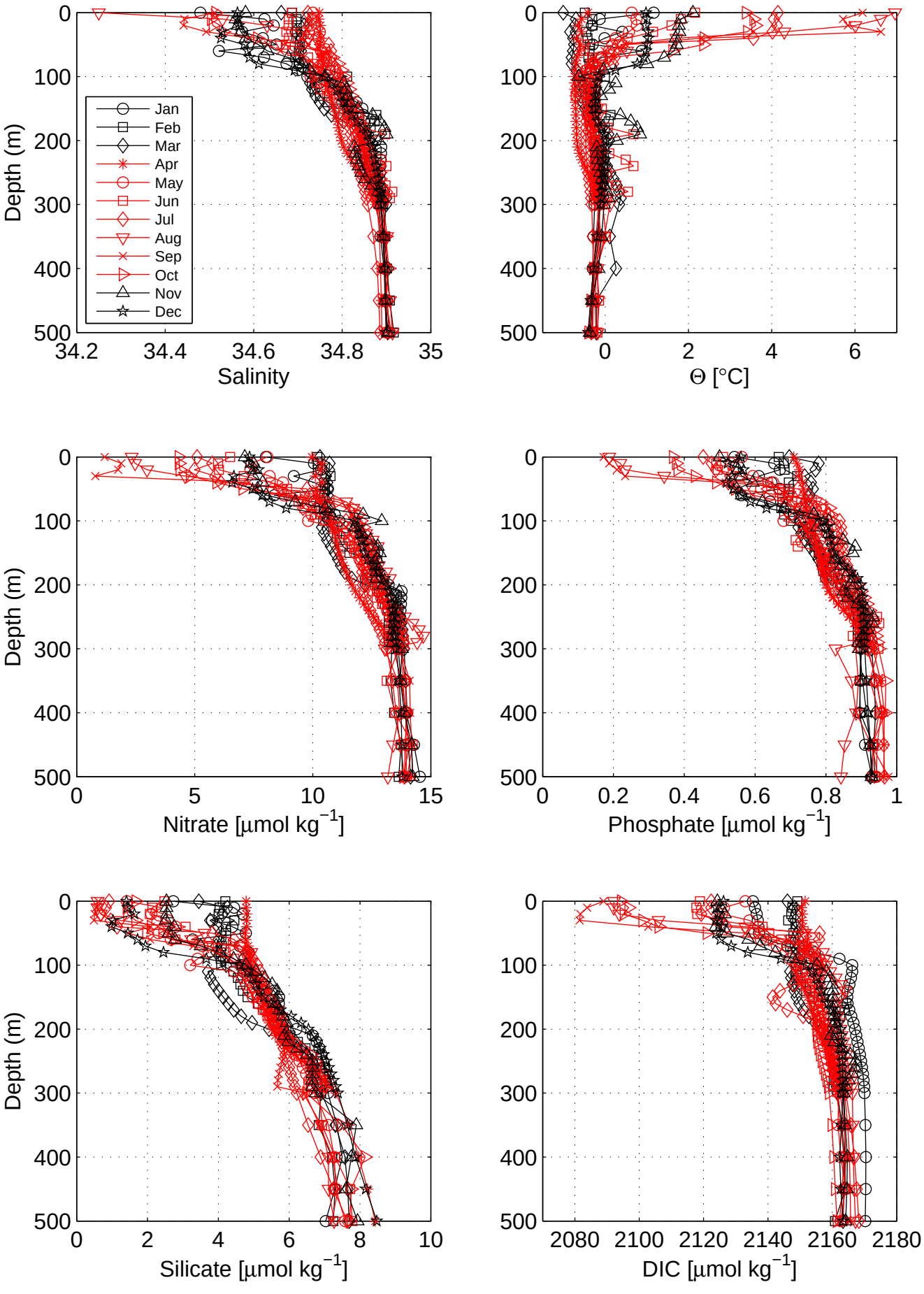
Depth (m)
0
100
200
300
400
500
Jan
Feb
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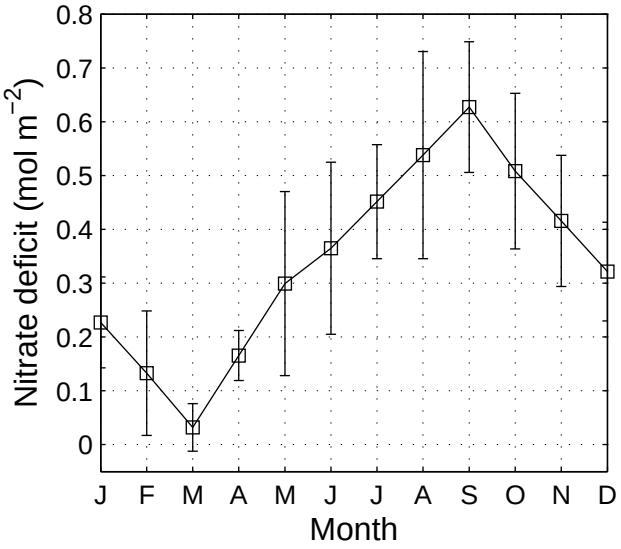
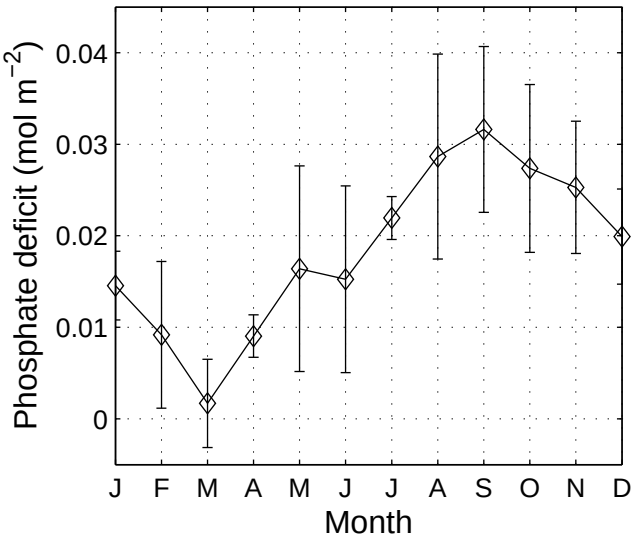
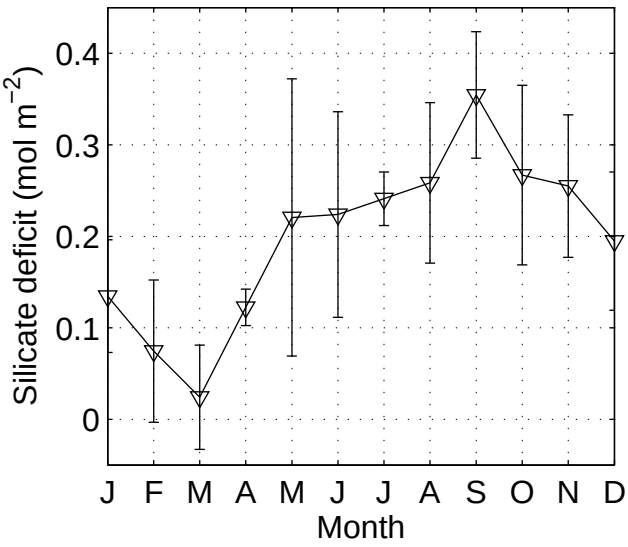
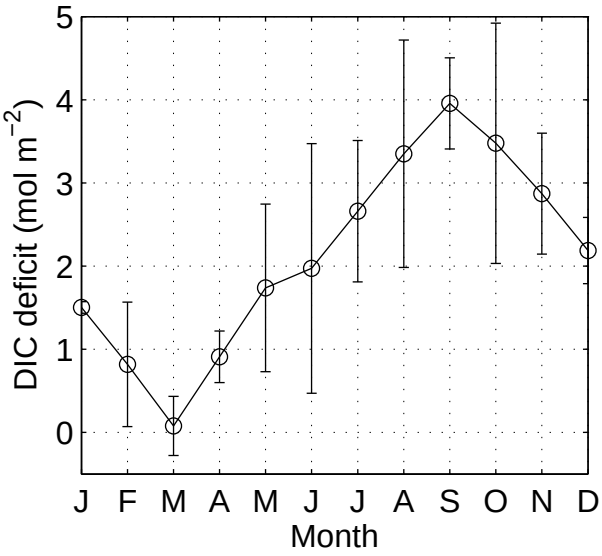
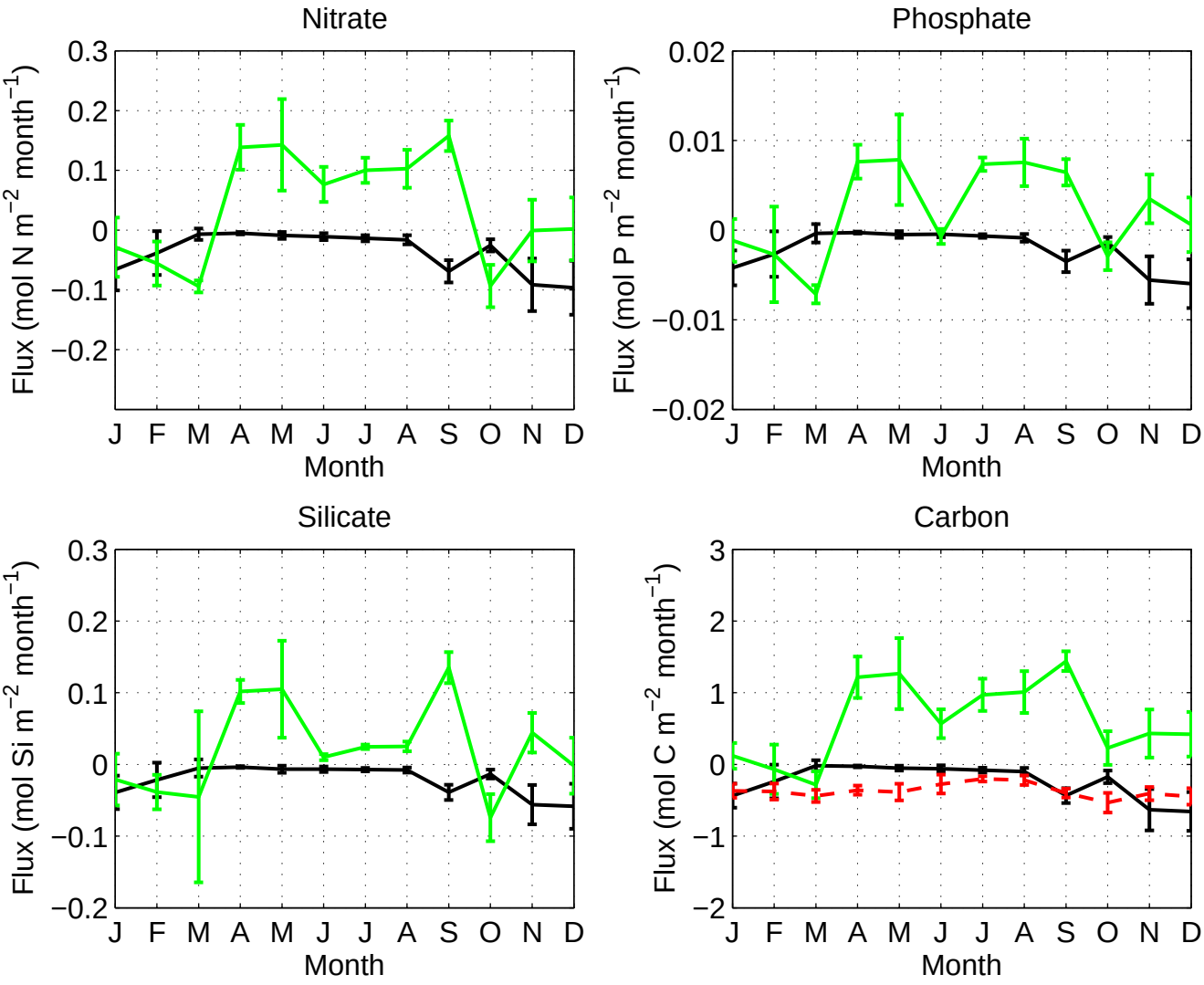
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
34.2
34.4
34.6
34.8
35
Salinity
0
2
4
6
Θ [°C]
0
5
10
15
Nitrate [µmol kg^{-1}]
0
0.2
0.4
0.6
0.8
1
Phosphate [µmol kg^{-1}]
0
2
4
6
8
10
Silicate [µmol kg^{-1}]
2080
2100
2120
2140
2160
2180
DIC [µmol kg^{-1}]

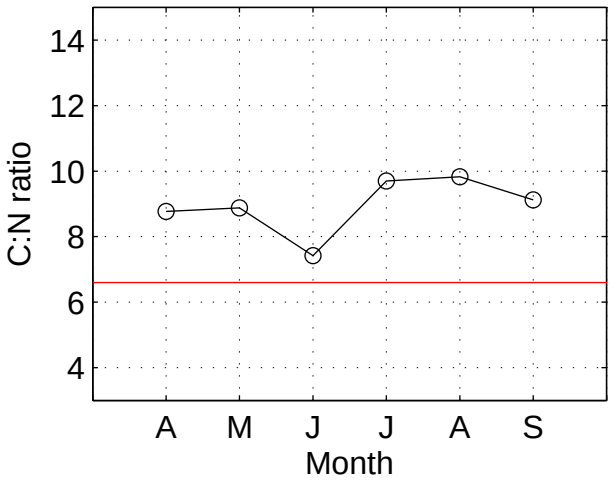

Nitrate deficit (mol m^{-2})
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
J F M A M J J A S O N D
Month

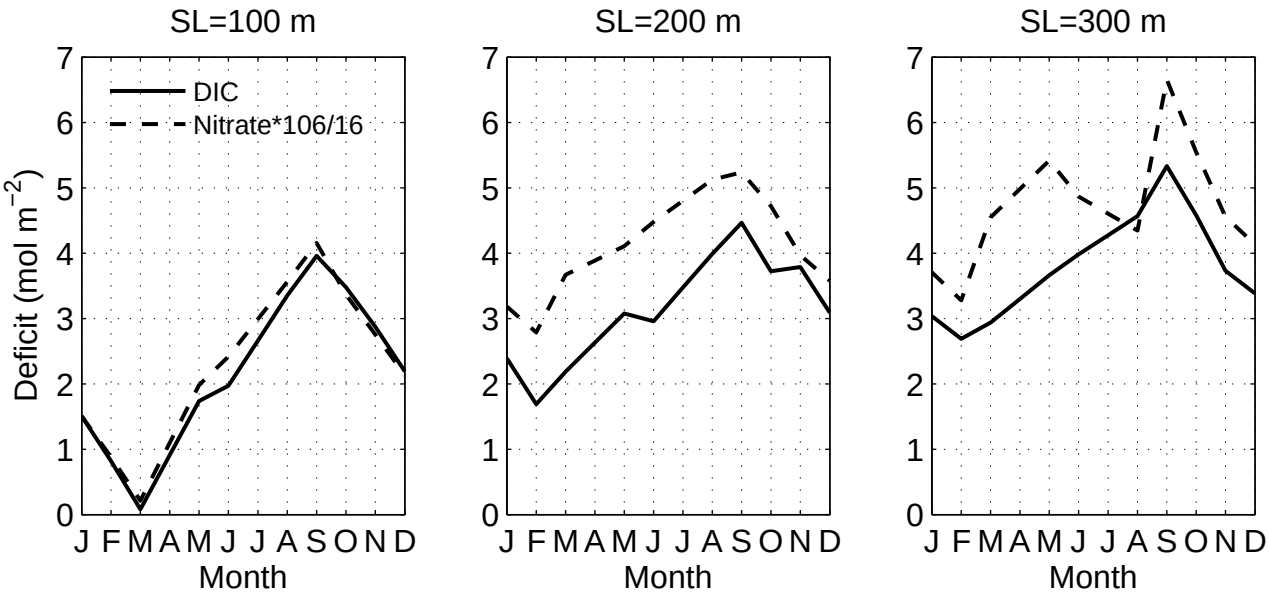

Phosphate deficit (mol m^{-2})
0.04
0.03
0.02
0.01
0
J F M A M J J A S O N D
Month


Silicate deficit (mol m^{-2})
0.4
0.3
0.2
0.1
0
J F M A M J J A S O N D
Month


DIC deficit (mol m^{-2})
5
4
3
2
1
0
J F M A M J J A S O N D
Month


Nitrate
Flux (mol N m^{-2} month^{-1})
0.3
0.2
0.1
0
−0.1
−0.2
J F M A M J J A S O N D
Month
Phosphate
Flux (mol P m^{-2} month^{-1})
0.02
0.01
0
−0.01
−0.02
J F M A M J J A S O N D
Month
Silicate
Flux (mol Si m^{-2} month^{-1})
0.3
0.2
0.1
0
−0.1
−0.2
J F M A M J J A S O N D
Month
Carbon
Flux (mol C m^{-2} month^{-1})
3
2
1
0
−1
−2
J F M A M J J A S O N D
Month


14
12
10
8
6
4
C:N ratio
A
M
J
J
A
S
Month


SL=100 m
SL=200 m
SL=300 m
DIC
Nitrate*106/16
Deficit (mol m^{-2})
0
1
2
3
4
5
6
7
J F M A M J J A S O N D
Month