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The importance of shelf processes for the modification of chemical constituents in the waters of the Eurasian Arctic Ocean: implication for carbon fluxes

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Abstract

Carbon transformation along the Eurasian shelves in water of Atlantic origin is estimated. Nutrient, oxygen, and inorganic and organic carbon data were used in the evaluation. By comparing the relative deficit of the different chemical constituents it is possible to evaluate the transformation of carbon. It can be seen that the chemical signature in the shelf seas was modified extensively, corresponding to an export production from the upper 50 m in the Barents Sea of 28–32 $\mathrm{g\,C\,m^{-2}}$, which is five times higher than that in the Kara–Laptev Seas and over the deep Eurasian basin. The difference in the export production, computed from the nutrient deficit, and the observed deficit of dissolved inorganic carbon is attributed air–sea exchange of CO_2. With this approach the relative oceanic uptake of CO_2 from the atmosphere was estimated to be 70% (44 $\mathrm{g\,C\,m^{-2}}$) in the Barents Sea and 15% (1 $\mathrm{g\,C\,m^{-2}}$) in the Kara–Laptev Seas, relative to the export production. Of the export production in the Barents Sea, about a quarter is found as DOC. The difference between the chemical signature at the Laptev Sea shelf slope and over the Lomonosov Ridge is negligible, which shows that the transformation of carbon is very small in the surface layers of the Eurasian basin. Combining the chemical transformation with reported volume transports gives an annual export production of $9.6 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ in the Barents Sea. The oceanic uptake of CO_2 for the same area is $9.2 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Shelf sea; Carbon dioxide system; Nutrients; Oxygen; Dissolved organic carbon; Export production

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1. Introduction

The warm and salty Atlantic Water flows into the Arctic Ocean through the Barents Sea. Here the water loses heat to the atmosphere and increases in salinity as a result of brine release during sea ice production. The resulting increase in density enables this water of Atlantic origin to penetrate to depths below 500 m when it enters the central Arctic Ocean through the St. Anna Trough (e.g. Swift et al., 1983; Schauer et al., 1997). In fact, much of the deep water that drives the global oceanic thermohaline circulation obtains its properties as a result of processes in the Arctic shelf seas, especially in the Barents Sea (Mauritzen, 1996). This deep water formation process is also potentially responsible for a significant sink of dissolved carbon, both inorganic and organic, to the deep global oceans. Hence, it is essential to understand the transformation of carbon in the shelf seas to estimate this sink and its sensitivity to environmental changes.

The Arctic shelf seas receive a large amount of river runoff ($1724\,\mathrm{km}^3\,\mathrm{yr}^{-1}$). The major rivers entering the Eurasian sector are the Ob, Yenisey and Lena (e.g. Olsson and Anderson, 1997). The latter enters the Laptev Sea, while the former two enter the Kara Sea. Most of the runoff entering the Kara Sea flows to the east along the continent, into the Laptev Sea, before flowing into the central Arctic Ocean (e.g. Olsson and Anderson, 1997). In the Kara Sea, the freshwater runoff is mixed with the more saline water of Atlantic origin that flows east over the shelves from the Norwegian Sea to the Laptev Sea (e.g. Jones et al., 1998). The runoff supplies the shelf seas with decay products from the drainage basins, including nutrients and dissolved inorganic as well as organic carbon (Anderson et al., 1990; Cauwet and Sidorov, 1996; Kattner et al., 1999). Furthermore, the runoff adds freshwater, inflow peaking in late spring/early summer which, together with sea ice melt, maintains stratification of the surface water during the productive summer season.

The volume of Atlantic Water that enters the central basin of the Arctic Ocean through the St. Anna Trough and the volume flowing through the Fram Strait are roughly similar (e.g. Rudels, 1987; Pfirman et al., 1994). The Atlantic Water that enters through Fram Strait follows the continental slope to the east, and when the water reaches the northern part of St. Anna Trough, a fraction turns southwards along the western flank of the St. Anna Trough. The remainder is forced away from the continental margin by the Barents Sea branch of Atlantic Water that enters the Arctic Ocean through the eastern part of the St. Anna Trough (e.g. Schauer et al., 1997). Further east, the water of Atlantic origin is deflected away from the continental margin and to a large degree it turns back towards Fram Strait within the Eurasian Basin (Rudels et al., 1994). Fig. 1 illustrates the main flow of the upper waters along the continental margins of the Eurasian part of the Arctic Ocean.

Total primary productivity in the central Arctic Ocean is estimated to $15\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, (Gosselin et al., 1997), but much of this might be recycled. New productivity is highest in the shelf seas of which the Barents Sea is considered to be one of the most productive, with a higher productivity along the marginal ice zone (Sakshaug and Skjoldal, 1989). As a result of the production patchiness, no estimate of the mean export production for the whole Barents Sea, based on measurements is available. However, the vertical carbon flux at 75 m as simulated by a 3-D model generally varied between $10–30\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ for a cold year (1981) and $20–40\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ for a warm year (1984) (Slagstad and Wassmann, 1996). Here, we estimate the carbon consumed in the water column as found after the water has passed through the Barents

Sea and the Kara–Laptev seas. Furthermore, by comparing the relative deficit of different constituents (nutrients, dissolved inorganic and organic carbon as well as oxygen) it is possible to evaluate the air-sea exchange of oxygen and carbon dioxide.

2. Methods

Data were collected during the Polarstern ARKXII (1996) cruise (Augstein, 1997) in the eastern Arctic Ocean as part of the Arctic Climate System Study (ACSYS). Sea water samples were collected at more than 100 stations (see Fig. 1) using a 36 bottle rosette equipped with a CTD probe, and were analysed for different chemical constituents. Complementary data west of the Barents Sea were collected during the Polarstern cruise ARK XI (1995) and the Johan Hjort cruise (May 1997 ESOP-2). In this study the concentration distribution of nutrients, oxygen, total alkalinity (A_T), total dissolved inorganic carbon (C_T) and dissolved organic carbon (DOC) are used. Standard analytical methods were used, where nutrients were measured using an autoanalyser and oxygen using automatic Winkler titration with photometric detection. A_T was analysed by titrating the sample with 0.05 M HCl and following the change in pH by the potentiometric method (Haraldsson et al., 1997). C_T was determined by gas extraction from an acidified sample followed by coulometric titration with photometric detection (Johnson et al.,

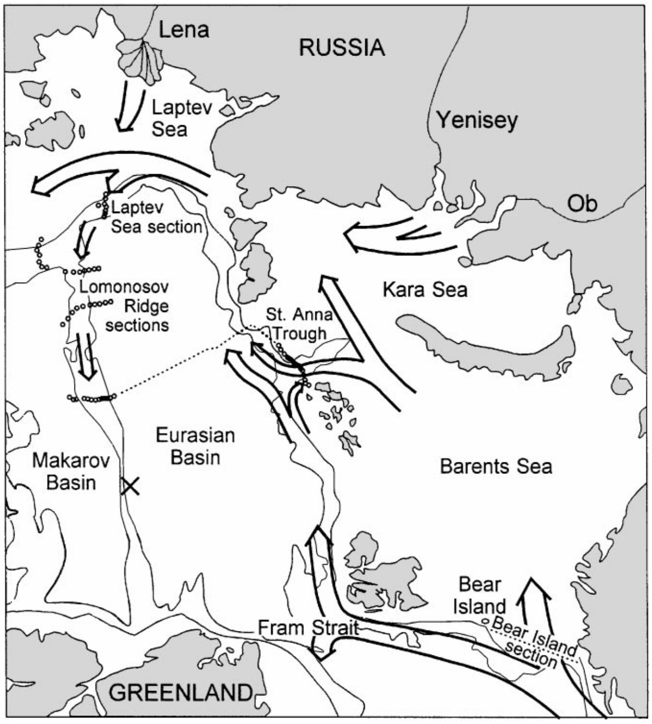

Fig. 1. Map illustrating the main flow of the upper waters along the continental margin in the Eurasian Basin of the Arctic Ocean and the location of the sampling stations of the ACSYS 96 cruise on RV Polarstern.

1985, 1987). The precision of C_T and A_T was obtained by replicate analysis. The accuracy was controlled by the use of certified reference material supplied by Andrew Dickson at SIO, USA. For the Polarstern ARK XII cruise the precision and accuracy for C_T and A_T was $\pm 2\,\mu\text{mol kg}^{-1}$ and for the Johan Hjort cruise $\pm 1\,\mu\text{mol kg}^{-1}$ for A_T and for C_T $\pm 2\,\mu\text{mol kg}^{-1}$. DOC was determined by high-temperature combustion, i.e. a Shimadzu TOC 5000 analyzer equipped with the standard 0.5% Pt catalyst. The injection volume was 100 μL with oxygen as carrier gas. The standard used was potassium hydrogen phthalate (Kanto Chemical Company, Inc.) (See Skoog et al., 1997). Precision of the measurements was 2.1%. DOC reference material from J. Sharp (University of Delaware, USA) showed the following results: Blank, 3.18 ± 2.18 μM C, $n = 11$; Deep Ocean, 44.77 ± 3.35 μM C, $n = 13$.

3. Results

3.1. Area of investigation

The areas studied in this investigation are the Barents and the Kara–Laptev Seas and the eastern Eurasian Basin. The positions of the stations used to estimate the transformation of carbon are shown in Fig. 1. A section between Bear Island and northern Norway represents the Atlantic water inflow to the Barents Sea, whereas the St. Anna Trough represents the outflow. The St. Anna Trough section represents the inflow from the Barents Sea to the Kara–Laptev Seas and a section north of the Laptev Sea represents the outflow. The sections over the Lomonosov Ridge further north are compared to the Laptev Sea section to evaluate changes in chemical signature in the surface layer over the deep eastern Eurasian Basin.

3.1.1. Bear Island to northern Norway section (70–76°N, 15–20°E)

The mean salinity of the entire water column in this section is 34.98 ± 0.06, and the freshwater contribution is therefore negligible. Assuming the winter water concentrations of nutrients and C_T along this section (i.e before the Atlantic Water enters the Barents Sea) as the preformed concentrations, the production that has occurred during the transport to St. Anna Trough can be estimated. Values below the euphotic zone should be representative of the winter surface concentrations, since this water would not have been subjected to any recent primary production. Nitrate, phosphate and C_T data, collected along the section in the summer of 1995 and spring of 1997 are used for the evaluation. The mean concentrations of the chemical constituents at 150–500 m depth are shown in Table 1.

3.1.2. St. Anna Trough section (81°N, 64–78°E)

The St. Anna Trough section shows a mixture of several water masses, as can be seen from the T–S diagram (Fig. 2). The most prominent water masses are a warm core ($T > 2°\text{C}$) of Atlantic water of Fram Strait origin (A), some less warm (around 1°C) Atlantic water entering through the Barents Sea (B), a high-density bottom water ($T \approx -0.3$ and $S \approx 34.89$ and $\sigma_0 \approx 28.04$) of Barents–Kara Seas origin (C), and relatively fresh surface water (D). The origin of the surface water is indicated by the depth profiles of salinity and temperature. At central stations (away from boundary currents) in the St. Anna Trough (Fig. 3), the surface water overlies the less warm

Table 1
Mean values in the eastern Norwegian Sea (70–76°N)

Constituent	Mean	Mean deviation
Temp (°C)	3.647	0.887
Salinity	34.98	0.062
Normalized C_T (μmol kg^{-1})	2146.2	4.2
Normalized A_T (μmol kg^{-1})	2319.4	21.4
Nitrate (μmol kg^{-1})	12.9	0.4
Phosphate (μmol kg^{-1})	0.88	0.04

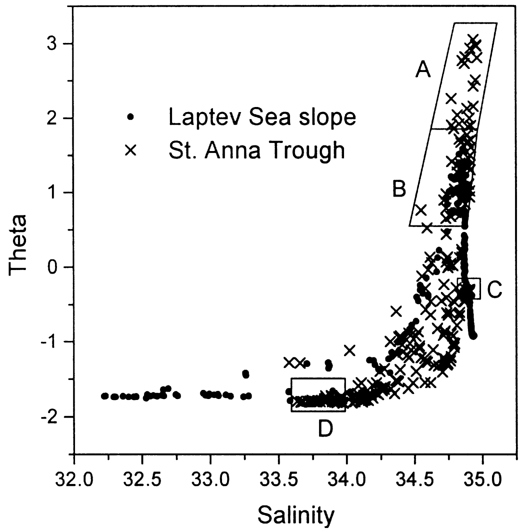

Fig. 2. $T-S$ diagram for all samples collected in the St. Anna Trough (X) and the Laptev Sea slope (●) sections. The St. Anna Trough section shows mixtures of source waters. Atlantic Layer water of Fram Strait (A) and Barents Sea (B) origin, bottom water of Barents–Kara Seas origin (C) and relatively fresh surface water (D).

Atlantic water that has entered through the Barents Sea. The upper 50 m (approximately where $S < 34$) at these stations is thus used to define the surface layer. Table 2 shows the mean values for the chemical parameters.

3.1.3. Laptev Sea section (78°N, 132–134°E)

Part of the Atlantic water that passes through the Barents Sea also continues through the Kara Sea and into the Laptev Sea, and mixes with river runoff (see Fig. 1). Some of this mixed water enters the Eurasian Basin north of the Laptev Sea (Schlosser et al., 1994), while some continues into the East Siberian Sea before turning into the central deep basin (Jones et al., 1998). The $T-S$ plot (Fig. 2) of this section shows the existence of similar water masses as in the St. Anna Trough section, but with a lower salinity of the surface water.

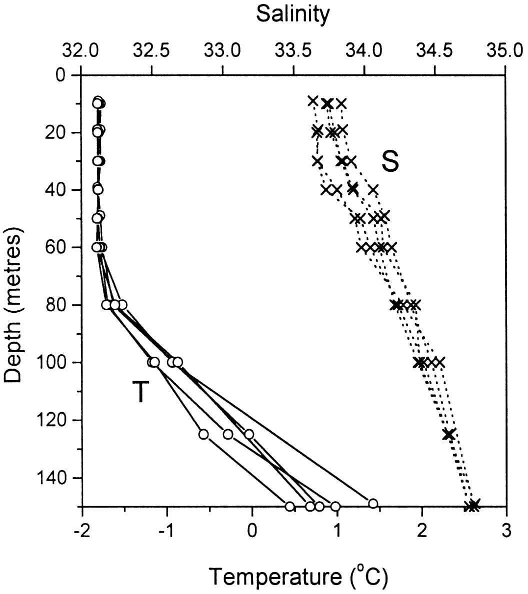

Fig. 3. Depth profiles of salinity and temperature in the upper 150 m of the central stations in the St. Anna Trough.

Table 2
Mean values of different constituents in the upper layer ($S < 34$) at the St. Anna Trough section

Constituent	Mean	Mean deviation
Theta (°C)	−1.764	0.050
Salinity	33.800	0.094
Oxygen (μmol kg^{-1})	350	4.4
Oxygen saturation (%)	95.6	1.4
Normalized C_T (μmol kg^{-1})	2200	6
Normalized A_T (μmol kg^{-1})	2321	8
Nitrate (μmol kg^{-1})	4.5	0.7
Phosphate (μmol kg^{-1})	0.48	0.05
pH-Hansson (at 15°C)	7.874	0.01

3.1.4. Lomonosov Ridge (81–86°N, 125–161°E)

The surface water from the Laptev Sea flows into the Eurasian Basin along the Lomonosov Ridge. Three data sections are used to evaluate the chemical transformation in the eastern Eurasian Basin. The $T-S$ plot for these sections (not shown) is nearly the same as the $T-S$ properties for the Laptev Sea section, indicating that the river runoff contribution is also similar.

3.2. Freshwater contribution

A general feature at all stations occupied during the Arctic 96 expedition is the lack of sea ice melt water in the surface layer. Two observations support this statement. First, the salinity profiles did not show any low salinity sea ice melt water layer, not even in 5 water samples taken within the top 1 m at the ice edge. Second, a linear correlation between the total alkalinity and salinity was found for all samples at depth less than 400 m (Fig. 4). If sea ice melt had contributed to the fresh water signal, a deviation from the straight line should be present, as no fractionation of alkalinity occurs when sea ice is formed or aged (e.g. Anderson and Jones, 1985).

In Arctic rivers the concentration of A_T is fairly high, typically above 1000 μmol kg^{-1} (Olsson and Anderson, 1997) and the intercept in the relationship between A_T and salinity is large. The result of combined decay of organic matter and dissolution of metal carbonates in the drainage basin, illustrated below for calcium, implies that the runoff has equal concentrations of A_T and C_T.

$$CH_2O(org) + CaCO_3(s) + O_2 \rightarrow 2HCO_3^- + Ca^{2+}. \tag{1a}$$

The relative amount of runoff can be computed if the average river runoff concentration of A_T is known, assuming conservative behavior. In well oxygenated water the relative concentration of A_T is barely affected, as long as no metal carbonate-producing plankton are present. In Arctic waters, the oxygen concentration is normally high (mostly >80% saturated) (Koltermann and Lüthje, 1989) and the dominating plankton species, diatoms and the dinoflagellate *Phaeocystis pouchetii* (Vernet et al., 1998), do not form carbonate shells.

During photosynthesis proteins are formed, where nitrate and hydrogen ions are consumed according to the reaction:

$$2CO_2 + NO_3^- + H^+ + H_2O \rightarrow NHCH_2CO(org) + 3.5O_2. \tag{1b}$$

In this study the maximum effect by this process on A_T is 10 μmol kg^{-1}, which is considered to be within the sensitivity of the calculations.

The mean total alkalinity concentration in the rivers adding to surface water of the area investigated can be evaluated by fitting a line in a A_T-S plot of all samples shallower than 400 m

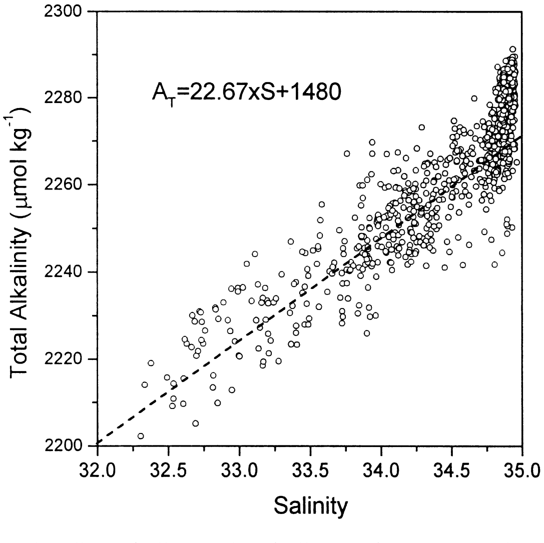

Fig. 4. A_T-S plot with linear regression line of all samples shallower than 400 m (close to the temperature maximum).

(at depth where the Atlantic layer dominates, i.e., where river water makes no contribution to A_T). The line with best fit is $A_T = 22.67 \times S + 1480$ ($R^2 = 0.7874$) (Fig. 4), and a concentration of 1480 μmol kg^{-1} should thus be a good mean to use for A_T in river runoff. The salinity of the seawater end member in the fit of this line is 34.85, corresponding to a A_T concentration of 2270 μmol kg^{-1}. To further investigate how much the sea-ice melt contributes to the water used for this study, we assume for multi-year sea ice a salinity of 5 (Untersteiner, 1986), which equals an A_T of 325 μmol kg^{-1}, if it is formed from a seawater of $S = 34.85$ without any fractionation. Hence, the relative fractions of seawater (f_{sw}), river runoff (f_{rro}) and sea ice melt (f_{sim}) can be computed from the following three equations:

$$1 = f_{\text{sw}} + f_{\text{rro}} + f_{\text{sim}}, \tag{2}$$

$$S = 34.85 f_{\text{sw}} + f_{\text{sim}} 5, \tag{3}$$

$$A_T = 2270 f_{\text{sw}} + 1480 f_{\text{rro}} + 325 f_{\text{sim}}. \tag{4}$$

A minor error is caused in this computation by the assumption that the sea ice is formed in a water of salinity equal 34.85. However, as the amount of sea ice melt is very low in all samples this error is of limited significance.

The freshwater distribution, relative $S = 34.85$, is shown in the top 150 m along the continental slope from the St. Anna Trough section to the Laptev Sea section (Fig. 5). At all sections the sea ice meltwater contribution is within about ±1%, which represents the uncertainty of the calculations. As can be seen from Fig. 5, three of the four sections have nearly the same profiles for river runoff. The St. Anna Trough section has much less river runoff than the other sections. Hence, there is a significant addition of runoff in the region between the St. Anna Trough and the Laptev Sea section (see Fig. 1 for positions).

3.3. Consumption of carbon

By knowing the concentrations of the chemical parameters in the source waters the preformed concentration, $c^{\text{preformed}}$, can be computed for each sample. Then we compare the preformed concentrations (inflowing water) with the measured ones, c^{measured}, in the outflowing water. This gives an estimate of the transformation which has occurred. When calculating the preformed oxygen concentration, the river runoff contribution is assumed to have a saturation value for freshwater at 0°C. Here follows an example for C_T in the Kara–Laptev Seas, where the river runoff fraction is significant and sea ice melt is negligible:

$$C_T^{\text{preformed}} = (1 - f_{\text{rro}}) C_T^{\text{StA}} + f_{\text{rro}} C_T^{\text{rro}} = (1 - f_{\text{rro}}) 2200 S/35 + f_{\text{rro}} 1480, \tag{5}$$

$$\Delta c = c_{\text{measured}} - c_{\text{performed}}. \tag{6}$$

As the sea ice melt contribution is low in all waters investigated (mostly below 1%), we neglect this contribution in the calculation of the preformed concentrations. Reported concentrations of nutrients in Siberian rivers vary, between different seasons but also within the season (Table 3) (Telang et al., 1991; Cauwet and Sidorov, 1996; Gordeev et al., 1996). However, with a maximum freshwater contribution of 8% and a residence time in the shelf seas of several years (Schlosser et al., 1994), this uncertainty will have a limited effect on the computed preformed concentration.

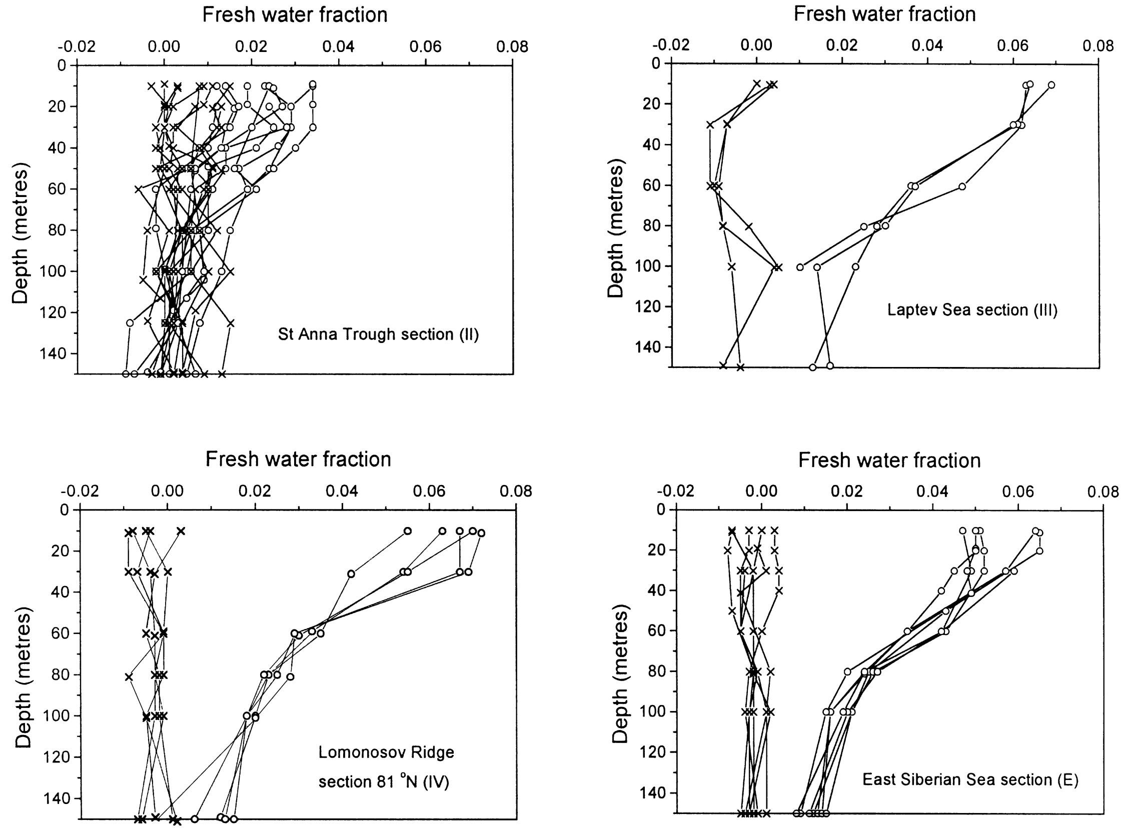

Fig. 5. The freshwater source distribution, relative to $S = 34.85$, in the top 150 m along the section St. Anna Trough, Laptev Sea slope, Lomonosov Ridge at 81°N and East Siberian Sea slope (see Fig. 1 for locations). The sea ice melt water and the river runoff are denoted as x and o, respectively.

Table 3
Mean river runoff concentrations of nutrients, entering the Arctic Ocean from the Eurasian continent (Telang et al., 1991; Cauwet and Sidorov, 1996; Gordeev et al., 1996)

Constituent	Concentration (μmol l^{-1})
Nitrate	4.6
Phosphate	0.45

The computed delta values for nitrate, phosphate and C_T would be negative if the constituent is consumed (signal of primary production) and positive if released (signal of remineralization). The delta value for oxygen follows the opposite relationship since oxygen is released during primary production and consumed during remineralization. The delta values (Δ) of C_T, N, P, O_2 for the studied area are then integrated for a specific depth interval, giving the corresponding consumption or release. To convert the integrated delta values of phosphate, nitrate and oxygen to carbon equivalents we have used the theoretical Redfield–Ketchum–Richards (RKR) ratio 1 : 16 : 106:-138 (P : N : C : O) (Redfield et al., 1963). The RKR study is based on the stoichiometric relationship of P : N : C in phytoplankton while other investigators (Anderson and Sarmiento, 1994; Schaffer, 1996) have related the ratios between nutrients, carbon and oxygen by looking at the decay of organic matter below the euphotic zone. This latter approach does not consider the nutrient consumption during production while the RKR ratios do not account for the vertical fractionation during remineralization. Since we calculate the exported carbon from the shelf seas by looking at the consumption of nutrients and carbon in the euphotic zone we apply the RKR ratios of P : N : C to 1 : 16 : 106.

Since nitrate is not affected by air–sea exchange as are the gaseous compounds of CO_2 and O_2, the production based on nitrate ($Prod_N$) and phosphate ($Prod_P$) deficits are taken as a reference when estimating the relative air–sea exchange of CO_2 and O_2. The production estimated from O_2, $Prod_O$, as well as from C, $Prod_C$, is compared with $Prod_N$ or ($Prod_P$) according to the formulas ($Prod_N$−$Prod_X$)/$Prod_N$) and ($Prod_P$−$Prod_X$)/$Prod_P$), where X represents either oxygen or carbon.

5. Discussion

5.1. Barents Sea

The delta profiles reveal that the water has been extensively modified by biochemical processes during its passage through the Barents Sea. Fig. 6 shows the delta values for phosphate, nitrate and C_T. The delta values in the surface layer suggest consumption, which indicates primary production, i.e. uptake by phytoplankton.

The integrated consumption of phosphate, nitrate and carbon is 0.022, 0.4 and 1.0 mol m^{-2} in the upper 50 m, respectively. The ratios 1 : 18 : 45 of the integrated values of P : N : C are in agreement with the classical Redfield ratio between phosphate and nitrate. However, the P : C ratio does not agree with RKR ratios, which implies that uptake of atmospheric CO_2 has occurred. By applying the RKR ratios for P : N : C of 1 : 16 : 106 to convert consumption of phosphate, nitrate and carbon into carbon equivalents, the consumption of inorganic carbon will correspond to an export production of 28, 32 and 12 g C m^{-2}, respectively.

Below 50 m the nutrient concentrations also show a deficit relative to the winter levels in the Norwegian Sea, indicating that primary production has occurred. Estimated export production in the surface 150 m results in a total of 53, 72 and 18 g C m^{-2} computed from P, N, and C, respectively, implying that 44 ± 10 g C m^{-2} has been taken up from the atmosphere. This signal has built up over the residence time of this water in the Barents Sea.

The above calculations do not consider the fate of the produced organic matter, which is either particulate matter or dissolved organic carbon. The concentration of DOC at depths shallower than 150 m in the St. Anna Trough increases towards the surface (Fig. 7), which is an indication of recent biological activity. The concentrations in the St. Anna Trough section can be compared with the ones in the Atlantic winter water, that enters the Barents Sea through the Bear Island section. In accordance to the nutrient data we can use the values from below the euphotic zone. However, the DOC concentration in the deep Norwegian Sea is typically 75 ± 11 μmol C l^{-1} (Børsheim and Myklestad, 1997), which is significantly higher than the mean value of

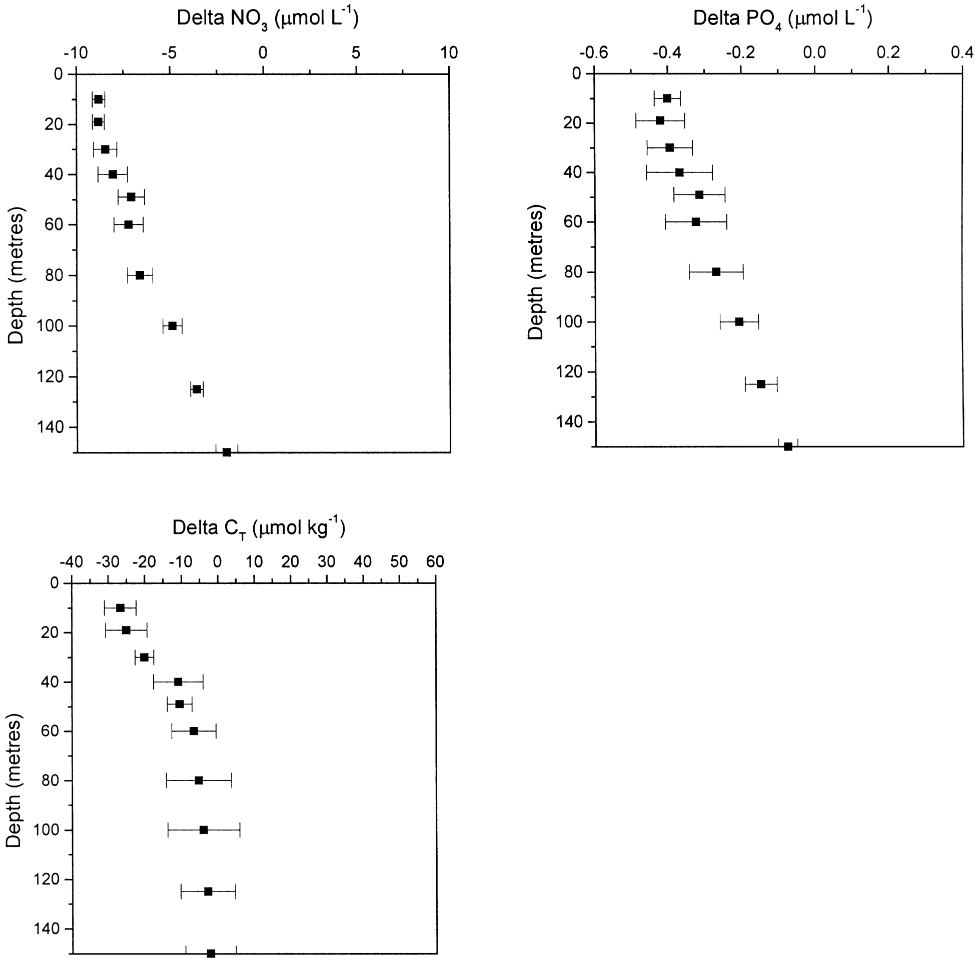

Fig. 6. Mean depth profiles of (a) delta nitrate, (b) delta phosphate and (c) delta dissolved inorganic carbon shown for the Barents Sea. The error bars represent the standard deviation. The delta values are the differences between measured and preformed concentrations.

52 ± 4 μmol C l^{-1} ($n = 12$) we find below 150 m depth in the St. Anna Trough. It is assumed that the St. Anna Trough deep water DOC represents the resistant part that is not easily used up by bacteria.

Subtracting the deep water concentration (mean equal 52 μmol C l^{-1}) from the DOC values (Fig. 7) gives the labile, i.e. freshly produced part of the DOC (Carlson and Ducklow, 1995; Hansell and Carlson, 1998). Integrated over the water column depth of 150 m, where the nutrient deficit indicates consumption, the labile part amounts to 17 g C m^{-2}, according to the method described in Hansell and Carlson (1998). A comparison of the labile DOC to the consumption of inorganic carbon as evaluated by the nutrient deficit (53–72 g C m^{-2}, mean 62 g C m^{-2}) shows that around 25% of the export production is in the form of recently produced DOC. It should be noted that, accepting that the DOC deep water concentration of 52 μmol C l^{-1} represents that of

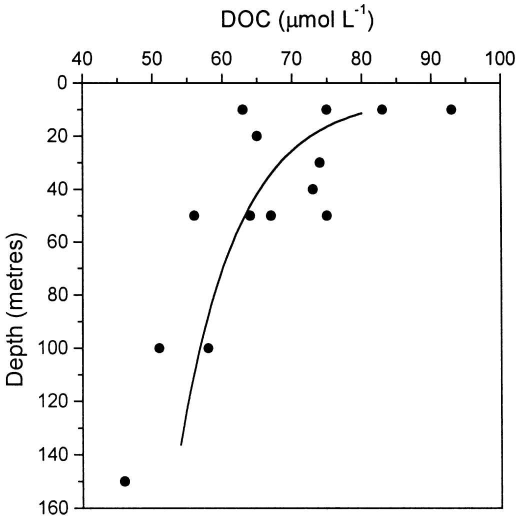

Fig. 7. Depth profile of DOC for the top 150 m of the St. Anna Trough.

the inflowing Atlantic water, this ratio is valid for the period of residence time of the water in the Barents Sea. Our estimated ratio is higher than the 12–15% reported for the Southern Ocean and Subarctic gyres (Hansell and Carlson, 1998). However, they state that the ratio is very sensitive to how the export or new production is calculated.

In summary, of the 62 ± 10 g C m^{-2} consumed, a deficit of 18 g C m^{-2} is observed in C_T and the remaining 44 g C m^{-2} is suggested to have been taken up from the atmosphere. Since we have no oxygen data for the inflowing Atlantic water, the air–sea exchange of oxygen cannot be estimated.

5.2. Kara–Laptev Seas

We compared the measured concentrations of the Laptev Sea section with the preformed values using Eqs. (5) and (6) and the concentrations in the upper layers of St. Anna Trough (Table 2) and the river runoff as source waters. The difference between the preformed and measured nitrate gives an estimate of the export production in the Kara and Laptev Seas. The profiles of delta oxygen, nitrate and inorganic carbon, together with salinity, are shown for the outer 3 stations in the Laptev Sea section (Fig. 8). The delta values for nitrate and C_T show consumption in the upper water column, for nitrate to 40–60 m, that is the depth of St. Anna Trough source water ($S = 33.8$). The phosphate data show too much scatter to be used in this discussion.

The mean integrated delta values for the top 50 m are −0.08 mol m^{-2} for nitrate, −0.45 for carbon and 0.55 for oxygen, giving a ratio of 16 : 90 : −110. If all data are converted to carbon equivalents, using the theoretical RKR ratio (1 : 16 : 106 : −138) the production along the route through the Kara and Laptev Seas corresponds to $\text{Prod}_N = 6.4$, $\text{Prod}_C = 5.4$ and $\text{Prod}_O = 5.1$ g C m^{-2}, respectively. The relative uncertainties within these numbers are in the order of 10%, related to how well the different station profiles agree. Thus, if the production based on the nitrate deficit, Prod_N, is taken as a reference, 20% of the produced oxygen has escaped to the atmosphere in order to achieve the same production, while about 15% of the

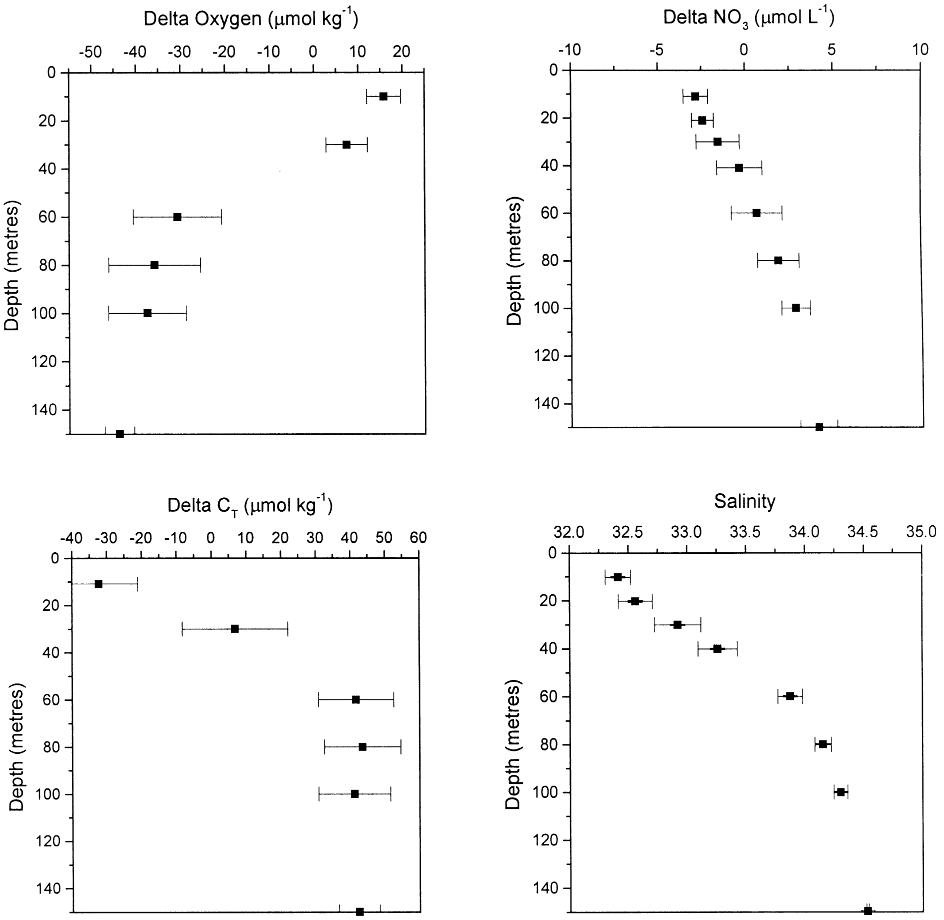

Fig. 8. Mean depth profiles of (a) delta oxygen, (b) delta nitrate, (c) delta dissolved inorganic carbon and (d) salinity in the Laptev Sea section. The error bars represent the standard deviations. The delta values are the difference between measured and preformed concentrations.

consumed carbon has been compensated for by uptake from the atmosphere. However, these numbers are within, or close to, uncertainty.

The sections in the Laptev Sea and over the Lomonosov Ridge are heavily influenced by riverine freshwater as seen in Fig. 5. The DOC concentration is high in runoff, giving an increased concentration with decreased salinity (Fig. 9) but it is also variable, both between rivers as well as between seasons. This combination makes it too uncertain to compute any preformed DOC concentration and no delta value was therefore estimated. The complex relationship between DOC and biological and hydrographic parameters in this region is described in more detail by Bussmann and Kattner (2000).

5.3. The eastern Eurasian Basin

The delta values for oxygen, nitrate, and C_T are for the Lomonosov Ridge section computed using the same preformed concentrations as for Laptev Sea section, i.e., the values in the upper

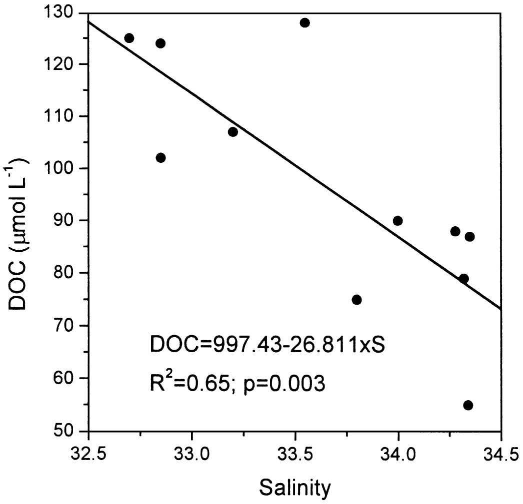

Fig. 9. DOC versus salinity for the surface stations of the section in the eastern Laptev Sea and for the Laptev Sea slope.

layer of the St. Anna Trough section and those in the river runoff. The delta values (Fig. 10) are close to the same as in the Laptev Sea section (Fig. 8), which shows that the major part of the biochemical transformation has already occurred in the Kara–Laptev Seas with a minor change in the eastern Eurasian Basin. The largest change is the increase of delta C_T in the upper 30 m, indicating uptake of atmospheric carbon dioxide.

5.4. Carbon signal in the deeper waters of Eurasian Basin

What is the fate of the organic matter that is produced? As shown before, the dissolved fraction of organic matter in the Barents Sea is limited to around 25% of the consumption, and thus two options are possible. The remainder is either buried in the sediment or is remineralized in the deeper layers of the central Arctic Ocean. To investigate the latter we compare the DOC concentrations in two deeper water masses sampled in the St. Anna Trough and along Lomonosov sections (Fig. 11): the Atlantic layer with temperature above 0°C and the Barents Sea bottom water with $S = 34.9$ and $T = -0.3°C$ (C in Fig. 2). In these deeper waters the DOC concentrations show no significant change from the St. Anna Trough to Lomonosov Ridge sections and neither do any of the other chemical constituents whose changes could be attributed to decay of organic matter. Consequently, the organic matter that is not buried must be remineralized at large depths (deeper than 1500 m) of the central Arctic Ocean.

The mean concentration of C_T in the deep waters (below 1500 m) of the Eurasian Basin is $8 \pm 9\,\mu\text{mol}\,\text{kg}^{-1}$ higher than in the overlying Atlantic Layer (Anderson et al., 1998). The ventilation rate of the waters below 1500 m depth is computed to $0.27 \times 10^6\,\text{m}^3\,\text{s}^{-1}$ by a plume entrainment model (Anderson et al., 1999), which implies that $0.4 \pm 0.4 \times 10^{12}$ g C is remineralized per year if a steady-state prevails.

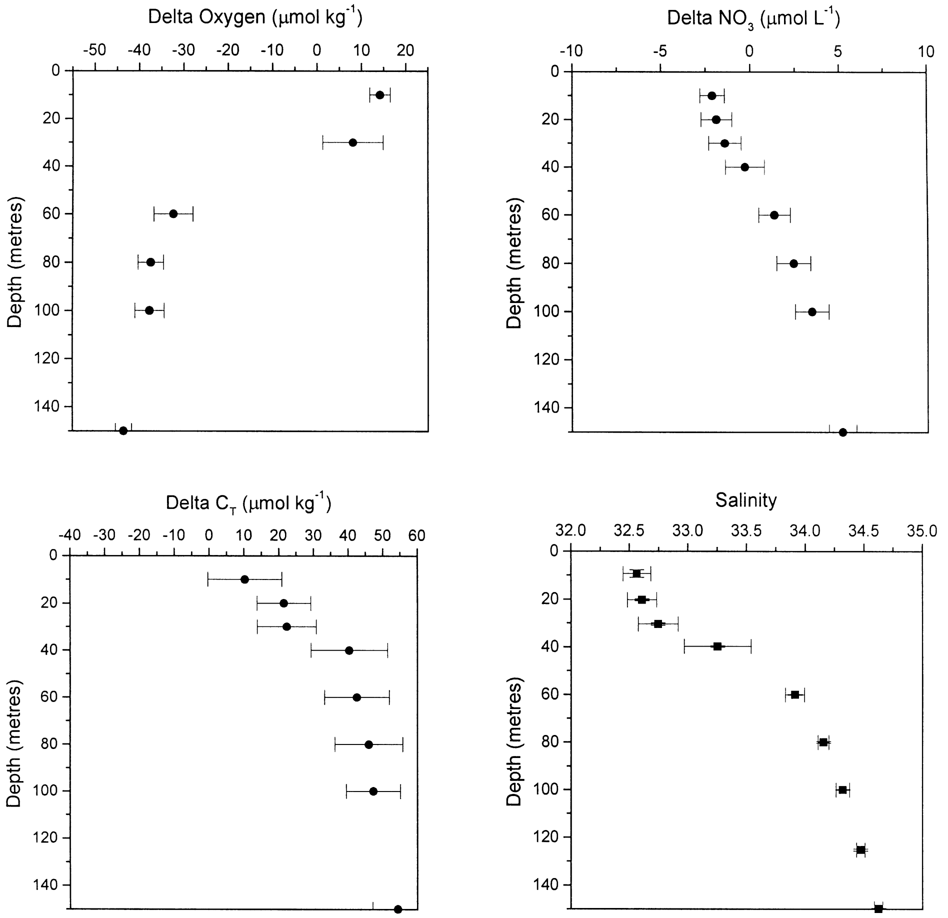

Fig. 10. Mean depth profiles of (a) delta oxygen, (b) delta nitrate, (c) delta dissolved inorganic carbon and (d) salinity in the Lomonosov Ridge section. The error bars represent the standard deviations. The delta values are the difference between measured and preformed concentrations.

5.5. Annual export production and air–sea exchange in the Barents Sea

By using the mean delta values of nitrate, converted to carbon equivalents, for the different layers representing the outflows of Barents Sea, we can calculate the export production in the Barents Sea. The outflow from the Barents Sea are, 0.16 Sv into the Laptev Sea (Olsson and Anderson, 1997), 0.2 Sv into the lower halocline (Schauer et al., 1997) and 0.85 Sv into the Atlantic layer (Schauer et al., 1997). Combining these volume flows with the computed deltas we get that $3.3 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ is exported to the Laptev Sea, $2.1 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ to the lower halocline and $4.2 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ to the Atlantic layer, giving a total of $9.6 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$.

Similarly, we compute the export of delta C_T, giving -1.3×10^{12}, -0.8×10^{12} and $1.7 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ to the same three water masses, respectively. Comparing the export of delta C_T with the export production, the difference of $9.2 \times 10^{12}\,\mathrm{g\,C\,yr^{-1}}$ corresponds to an oceanic

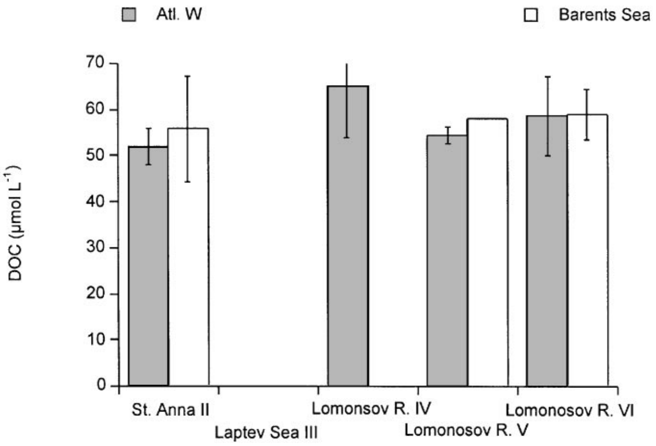

Fig. 11. The DOC concentrations for the two deeper water masses in the St. Anna Trough and the Lomonosov ridge sections.

uptake of atmospheric carbon dioxide. The total atmospheric input to the entire Arctic Ocean has earlier been reported as $24\times10^{12}\,\mathrm{g\,C\,yr^{-1}}$(Anderson et al., 1998). Thus, the Barents Sea contributes about a third of the oceanic uptake of CO_2 in the Arctic Ocean. The area of the Barents Sea ($1.4\times10^{12}\,\mathrm{m^2}$) constitutes 10% of the total area for the Arctic Ocean ($14\times10^{12}\,\mathrm{m^2}$). This implies that the sequestering of atmospheric CO_2 in the Barents Sea is higher than in the Arctic Ocean on an areal basis.

6. Conclusions

A comparison along the lateral flow patterns of the water masses along the Eurasian shelves gives an estimate on the biochemical transformations that have occurred along transport. The highest export production (transformation) occurs in the Barents Sea with 28–32 $\mathrm{g\,C\,m^{-2}}$ in the top 50 m, while production on the Kara and Laptev Sea shelves in the same depth interval is five times less. The export production over the eastern Eurasian Basin is negligible. This emphasizes that, considering the general circulation pattern, the transformation processes in the Barents Sea dominate those in the Kara–Laptev shelf seas.

The observed changes of C_T, nitrate and oxygen in the Kara and Laptev Seas are close to the classic RKR ratio, indicating that little net air–sea exchange of CO_2 and oxygen occurs in this region. In the Barents Sea the observed consumption of nitrate relative to C_T deviates from the RKR ratio, requiring an oceanic CO_2 uptake of about 70% (44 $\mathrm{g\,C\,m^{-2}}$) of the export production.

Combining the chemical transformation with reported volume transports the annual export production equals $9.6\times10^{12}\,\mathrm{g\,C\,yr^{-1}}$ in the Barents Sea. The oceanic uptake of CO_2 for the same area results in $9.2\times10^{12}\,\mathrm{g\,C\,yr^{-1}}$.

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References

Anderson, L.A., Sarmiento, J.L., 1994. Redfield ratios of remineralisation determined by nutrient data analysis. Global Biogeochemical Cycles 8, 65–80.

Anderson, L.G., Jones, E.P., 1985. Measurements of total alkalinity, calcium and sulfate in natural sea ice. Journal of Geophysical Research 90, 7355–7360.

Anderson, L.G., Dyrssen, D., Jones, E.P., 1990. An assessment of the transport of atmospheric CO_2 into the Arctic Ocean. Journal of Geophysical Research 95, 1703–1711.

Anderson, L.G., Olsson, K., Chierici, M., 1998. A carbon budget for the Arctic Ocean. Global Biogeochemical Cycles 12, 455–465.

Anderson, L.G., Jones, E.P., Rudels, B., 1999. Ventilation of the Arctic Ocean estimated by a plume entrainment model constrained by CFCs. Journal of Geophysical Research 104,13, 423–13,429.

Augstein, E., 1997. The expedition ARCTIC '96 of RV Polarstern (ARK XII) with the Arctic Climate System Study (ACSYS), Reports on Polar Research, 234, Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany, 54pp.

Børsheim, K.Y., Myklestad, S.M., 1997. Dynamics of DOC in the Norwegian Sea inferred from monthly profiles collected during 3 years at 66°N, 2°E. Deep-Sea Research 44 (4), 593–601.

Bussmann, I., Kattner, G., 2000. Distribution of dissolved organic carbon in the central Arctic Ocean. Journal of Marine Systems 27, 209–219.

Carlson, C.A., Ducklow, H.W., 1995. Dissolved organic carbon in the upper ocean of the central equatorial Pacific Ocean, 1992: daily and fine scale vertical variations. Deep-Sea Research 42 (2–3), 639–656.

Cauwet, G., Sidorov, I., 1996. The biogeochemistry of Lena River: organic carbon and nutrients distribution. Marine Chemistry 53, 211–227.

Gordeev, V.V., Martin, J.M., Sidorov, I.S., Sidorova, M.V., 1996. A reassessment of the Eurasian River input of water, sediment, major elements, and nutrients to the Arctic Ocean. Journal of American Sciences 296, 664–691.

Gosselin, M., Levasseur, M., Wheeler, P.A., Horner, R.A., Booth, B.C., 1997. New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep-Sea Research 44, 1623–1644.

Hansell, D.A., Carlson, C.A., 1998. Net community production of dissolved organic carbon. Global Biogeochemical Cycles 12, 443–453.

Haraldsson, C., Anderson, L.G., Hassellöv, M., Hulth, S., Olsson, K., 1997. Rapid, high-precision potentiometric titration of alkalinity in the ocean and sediment pore waters. Deep-Sea Research I 44, 2031–2044.

Johnson, K.M., King, A.E., Sieburth, J.M., 1985. Coulometric TCO_2 analyses for marine studies: an introduction. Marine Chemistry 16, 61–82.

Johnson, K.M., Sieburth, J.M., Williams, P.J., Brandstrom, L., 1987. Coulometric total carbon dioxide analysis for marine studies: automation and calibration. Marine Chemistry 21, 117–133.

Jones, E.P., Anderson, L.G., Swift, J.H., 1998. Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation. Geophysical Research Letter 25, 765–768.

Kattner, G., Lobbes, J.M., Fitznar, H.P., Engbrodt, R., Nöthig, E.-M., Lara, R.J., 1999. Tracing dissolved organic substances and nutrients from the Lena River through Laptev Sea (Arctic). Marine Chemistry 65, 25–39.

Koltermann, K.P., Lüthje, H., 1989. Hydrographischer Atlas der Grönland und Nördlichen Norwegischen See (1979–1987). Deutsches Hydrographisches Institute, Hamburg, 274pp.

Mauritzen, C., 1996. Production of dense overflow waters feeding the North Atlantic across the Greenland–Scotland Ridge. Part 1: evidence for a revised circulation scheme. Deep-Sea Research 43, 769–806.

Olsson, K., Anderson, L.G., 1997. Input and biogeochemical transformation of dissolved carbon in the Siberian shelf seas. Continental Shelf Research 17, 819–833.

Pfirman, S.L., Bauch, D., Gammelsrød, T., 1994. The Northern Barents Sea: water mass distribution and modification. In: Johannessen, O.M., Muench, R.D., Overland, J.E. (Eds.), The Polar Oceans and Their Role in Shaping the Global Environment. American Geophysical Union, Washington, DC, pp. 77–94.

Redfield, A.C., Ketchum, B.H., Richards, F.A., 1963. The influence of organisms on the composition of sea water. In: Hill, M.N. (Ed.), The Sea, Vol. 2. Wiley, New York, pp. 26–77.

Rudels, B., 1987. On the mass balance of the Polar Oceans, with special emphasis on the Fram Strait. Norsk Polarinstitutt Skrifter 188, 1–53.

Rudels, B., Jones, E.P., Anderson, L.G., Kattner, G., 1994. On the intermediate depth waters of the Arctic Ocean. In: Johannessen, O.M., Muench, R.D., Overland, J.E. (Eds.), The Polar Oceans and Their Role in Shaping the Global Environment. American Geophysical Union, Washington, DC, pp. 33–46.

Sakshaug, E., Skjoldal, H.R., 1989. Life at the ice edge. Ambio 18, 60–67.

Schaffer, G., 1996. Biogeochemical cycling in the global ocean 2. New production, Redfield ratios and remineralization in the organic pump. Journal of Geophysical Research 101, 3723–3745.

Schauer, U., Muench, R., Rudels, B., Timokhov, L., 1997. The impact of Eastern Arctic shelf waters on the Nansen Basin intermediate layers. Journal of Geophysical Research 102, 3371–3382.

Schlosser, P., Bauch, D., Fairbanks, R., Bönisch, G., 1994. Arctic river-runoff: mean residence time on the shelves and in the halocline. Deep-Sea Research 41, 1053–1068.

Skoog, A., Thomas, D., Lara, R., Richter, K.-U., 1997. Methodological investigations on DOC determinations by the HTCO method. Marine Chemistry 56, 39–44.

Slagstad, D., Wassmann, P., 1996. 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 51, 119–141.

Swift, J.H., Takahashi, T., Livingstone, H.D., 1983. The contribution of the Greenland and Barents Seas to the deep water of the Arctic Ocean. Journal of Geophysical Research 88, 5981–5986.

Telang, S.A., Pocklington, R., Naidu, A.S., Romankevich, E.A., Gitelson, I.I., Gladyshev, M.I., 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian Rivers: the St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan Rivers, the Arctic Basin Rivers in the Soviet Union, and the Yenisei. In: Degens, E.T., Kempe, S., Richey, J.E. (Eds.), Biogeochemistry of Major World Rivers. Wiley, New York, pp. 75–104.

Untersteiner, N., 1986. Types of ice. In: Untersteiner (Ed.), The Geophysics of Sea Ice. Series B, Physics. NATO ASI Series, Plenum Press, New York, pp. 5–29 (Chapter 2).

Vernet, M., Matrai, P.A., Andreassen, I., 1998. Synthesis of particulate and extracellular carbon by phytoplankton at the marginal ice zone in the Barents Sea. Journal of Geophysical Research 103, 1023–1037.