

Biogeosciences Discussions is the access reviewed discussion forum of *Biogeosciences*

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Carbon cycling in the Arctic Archipelago: the export of Pacific carbon to the North Atlantic

E. H. Shadwick¹, T. Papakyriakou², A. E. F. Prowe³, D. Leong¹, S. A. Moore¹, and
H. Thomas^{1,4}

¹Department of Oceanography, Dalhousie University, Halifax NS, Canada

²Center for Earth Observation Science, University of Manitoba, Winnipeg MB, Canada

³Leibniz-Institut für Meereswissenschaften, IFM-GEOMAR, 24105 Kiel, Germany

⁴NSERC Canada Research Chair in Marine Biogeochemistry, Canada

Received: 19 November 2008 – Accepted: 19 November 2008 – Published: 16 January 2009

Correspondence to: E. H. Shadwick (elizabeth.shadwick@dal.ca)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The Arctic Ocean is expected to be disproportionately sensitive to climatic changes, and is thought to be an area where such changes might be detected. The Arctic hydrological cycle is influenced by: runoff and precipitation, sea ice formation/melting, and the inflow of saline waters from Bering and Fram Straits and the Barents Sea Shelf. Pacific water is recognizable as intermediate salinity water, with high concentrations of dissolved inorganic carbon (DIC), flowing from the Arctic Ocean to the North Atlantic via the Canadian Arctic Archipelago. We present DIC data from an east-west section through the Archipelago, as part of the Canadian International Polar Year initiatives. The fractions of Pacific and Arctic Ocean waters leaving the Archipelago and entering Baffin Bay, and subsequently the North Atlantic, are computed. The eastward transport of carbon from the Pacific, via the Arctic, to the North Atlantic is estimated.

Altered mixing ratios of Pacific and freshwater in the Arctic Ocean have been recorded in recent decades. Any climatically driven alterations in the composition of waters leaving the Arctic Archipelago may have implications for anthropogenic CO₂ uptake, and hence ocean acidification, in the subpolar and temperate North Atlantic.

1 Introduction

In recent years much research has been devoted to understanding the ocean carbon cycle because of its prominent role in controlling global climate. More than 98% of the carbon in the atmosphere-ocean system is in the ocean; small changes in the ocean carbon cycle can therefore greatly influence atmospheric carbon dioxide (CO₂) concentration.

The Arctic Ocean is expected to be disproportionately responsive to climate changes. High latitude oceans are ecologically sensitive areas where the early detection of climatic changes may be possible. Much attention has been given to the oceans' ability to sequester anthropogenic carbon dioxide, and regions of deep water

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



formation are of particular importance for this process. Change sentence to: Seasonally ice-covered waters are sites of exceptionally high heat exchange, and may therefore potentially transfer carbon dioxide into the deep ocean with greater efficiency than their lower latitude counterparts (Smith and Gordon, 1997; Miller et al., 2002).

5 As such, the Arctic Ocean, and its carbon cycle in particular have been the subject of much recent study (Anderson et al., 1998a, b; Fransson et al., 2001; Miller et al., 2002; Bates et al., 2005).

A greater understanding of the linkage between the export of freshwater from the Arctic Ocean to the North Atlantic and the North Atlantic Oscillation (NAO) has emerged in recent years (Kwok, 2000; Peterson et al., 2002; Anderson et al., 2004; Peterson et al., 2006; Greene and Pershing, 2007). A high NAO index enhances and diverts the prevailing westerly winds, causing an eastward shift of the Eurasian river discharge and greater precipitation over Northern Europe (Thompson and Wallace, 2001). This eastward diversion of Eurasian runoff has been linked to a freshening of the Canada Basin (Macdonald et al., 2002). The export of freshwater from the Arctic to the North Atlantic is dominated by transport through the Canadian Arctic Archipelago and through Fram Strait (Serreze et al., 2006). Changes in this freshwater export are expected to have consequences for North Atlantic Deep Water formation (Rahmstorf, 2002).

20 It has been suggested that the decline in CO₂ uptake in the subpolar and temperate North Atlantic Ocean in the last decade is linked to the low or neutral NAO index over the same period. The NAO driven export of water high in dissolved inorganic carbon (DIC) from the Arctic Ocean has implications for the uptake of atmospheric CO₂ in the North Atlantic, particularly in the northwestern region (Thomas et al., 2008). An understanding of the distribution and cycling of DIC in the waters of the Canadian Arctic Archipelago is therefore of great importance to an understanding of carbon cycling in the Arctic Ocean as a whole. In the present paper, observed concentrations of DIC from west of Banks Island, eastward through the Archipelago to Jones and Lancaster Sounds, are exploited to reveal the mixing between five dominant water masses. The

Carbon cycling in the Arctic ArchipelagoE. H. Shadwick et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

relative contributions of river, Arctic, Pacific, and two sources of Atlantic water: from the West via the Beaufort Sea, and from Baffin Bay via the West Greenland Current, flowing out of the Archipelago and into Baffin Bay are determined and the corresponding eastward transport of carbon is estimated.

2 Data and methods

2.1 Sample collection and analysis

Samples were collected at 31 stations throughout the Canadian Archipelago from Baffin Bay westward to Banks Island (Fig. 1) during September and October, 2007. Approximately 500 samples were collected from the entire water column, with higher vertical resolution within the euphotic zone, at all stations shown in Fig. 1. Dissolved inorganic carbon (DIC) samples were tapped from 12 l Niskin bottles mounted on a General Oceanic 24-bottle rosette fitted with SeaBird CTD such that all chemical data are associated with high precision in-situ temperature, salinity and oxygen data. Following water collection, DIC samples were poisoned with a solution of supersaturated HgCl_2 to halt biological activity, and stored in the dark, at 4°C, to await analysis.

All samples were analyzed on board by coulometric titration using a VINDTA 3C (Versatile Instrument for the Determination of Titration Alkalinity, by Marianda). Analytical methods for determination of DIC have been fully described elsewhere (Johnson et al., 1993; Fransson et al., 2001; Bates et al., 2005). Routine analyses of Certified Reference Materials (provided by A. G. Dickson, Scripps Institution of Oceanography) ensured that the uncertainty of the DIC measurements was less than 1.5%.

2.2 Water mass definitions

Atlantic water enters the Arctic Ocean through Fram Strait and the Barents Sea. Pacific water enters the Arctic Ocean through the Bering Strait and via the Chukchi Sea.

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

River inflow to the Arctic is dominated by Eurasian rivers, with their North American counterparts playing a smaller, though still significant, role. Atlantic water enters the Canadian Archipelago, in relatively small quantities, at the surface from the East via Nares Strait, and more significantly, as deep water from the west via the Beaufort Sea and the Canada Basin. Pacific water enters from the West, and river runoff enters the Archipelago from the numerous terrestrial sources, the largest of these being the Yukon and Mackenzie Rivers.

Previous studies have reported various classifications and names for the portions of the Arctic Ocean water column (Anderson et al., 1994; Jones et al., 1998; Ekwurzel et al., 2001; Ingram et al., 2002; McLaughlin et al., 2004). In the data set reported here, salinity and DIC concentrations of discrete samples revealed a mixing of four source waters: river runoff or terrestrial water, Arctic Ocean water, Pacific Ocean water, and Atlantic Ocean water (Fig. 2). We here define river runoff (or water of terrestrial origin) as having $S < 29$, Arctic water as having $28 < S < 32$ (following the range of salinity values for the Canada Basin reported by Yamamoto-Kawai and Tanaka, 2005), Pacific water as having salinity $S = 33.1$ (following Macdonald et al., 2002 and McLaughlin et al., 2004), and Atlantic water as having salinity of $S > 34$.

The DIC value for our river runoff end member, (denoted by subscript rro), of salinity $S_{\text{rro}} = 0$ was determined by fitting a regression line for all DIC samples with $S < 29$ and taking the intercept at $S = 0$. The resulting DIC value for our zero-salinity end member is in agreement with the estimate of Hansell et al. (2004) for the Beaufort Sea. The other end member properties are the mean value of several samples with characteristic salinities of Arctic, Pacific, and Atlantic water. End member properties are given in Table 1.

While there has been some debate as to the utility of the salinity normalization in the analysis of water mass properties, particularly in the coastal zone (Friis et al., 2003; Robbins, 2001), we here find that salinity normalized DIC, (DIC_{norm}), is useful parameter in the identification of water masses and conservative mixing relationships. In the subsequent analysis, DIC normalized to a regional mean salinity of $S^{\text{mean}} = 32.5$,

(i.e. $DIC_{norm}=32.5DIC/S$) is reported (Figs. 2 and 4). Data with salinity $S<29$ were normalized using a non-zero freshwater end-member using Eq. (1) and following Friis et al. (2003):

$$DIC_{norm} = \frac{(DIC^{obs} - DIC^{S=0})}{S^{obs}} S^{mean} + DIC^{S=0}, \quad (1)$$

5 where the superscript “obs” refers to the observed value.

2.3 Mixing analysis

In general, knowing the salinity and DIC of the four sources: river runoff, Arctic, Pacific, and Atlantic water, one can compute their relative fractions in a seawater sample with known salinity and DIC. Using the aforementioned end-member properties and
 10 assuming three end member mixing, a version of the following equations may be used to compute the relative fractions of river runoff (f_{rro}), Arctic (f_{arc}), Pacific (f_{pac}) and Atlantic water (f_{atl}) in a given sample of known salinity (S) and DIC concentration (DIC). Not all waters have a third source water component. The following three component mass balance equations were solved for all samples to determine which waters had,
 15 for example, an Arctic, Pacific and Atlantic component.

$$1 = f_{arc} + f_{pac} + f_{atl} \quad (2)$$

$$S = S_{arc}f_{arc} + S_{pac}f_{pac} + S_{atl}f_{atl} \quad (3)$$

$$DIC = DIC_{arc}f_{arc} + DIC_{pac}f_{pac} + DIC_{atl}f_{atl} \quad (4)$$

If the three-component solution results in a negative value of, for example, runoff
 20 fraction (f_{rro}), then river runoff was not present, and in this case the two component mass balance system would be solved for this sample.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Results

3.1 Profiles of dissolved inorganic carbon

The distribution of DIC with depth in three regions Fig. 3: (a) West of Banks Island, near the Canada Basin; (b) centrally located in the Canadian Archipelago; and (c) near the outflow of Lancaster Sound to Baffin Bay. River runoff was found only in near surface waters at those stations located very close to land. Arctic water is predominantly seen in the depth range of 30 to 100 m, and is fairly evenly distributed longitudinally, though the depth of penetration decreases eastward through the Archipelago. High contributions of Pacific water are seen in the range of 80 to 200 m at the westernmost stations, while the more easterly stations show slightly lesser contributions with a fairly significant fraction of Pacific water penetrating down to depths of greater than 400 m. Atlantic water dominates the water column at depths greater than 200 m; the highest fraction is found at the westernmost stations, entering the Canadian Archipelago as deep water via the Beaufort Sea. The DIC concentration is notably higher at the depth of 200 m in centrally located station than is seen at the same depth in the more western station. We propose that organic matter remineralization over the shallow sill at the central location is the reason for the increased concentrations seen there.

Atlantic water was also found at stations located in Lancaster and Jones Sounds, comprising between 32% and 54% of the water column (see Table 2). However, this is Atlantic water coming via the West Greenland Current (WGC) in the Labrador Sea, and not Atlantic water leaving the Arctic ocean as deep water from the Beaufort Sea.

3.2 Mixing of water masses

In the plot of salinity normalized DIC versus salinity, five mixing regimes are revealed (Fig. 4). Mixing of river runoff, or water of terrestrial origin, with Arctic water was primarily observed in the surface waters of the westernmost stations and throughout the water column at those few stations located very close to the North American continent.

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic ArchipelagoE. H. Shadwick et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Mixing of Arctic and Pacific waters, with, in some cases a third source of river runoff, was observed at most stations in the depth range of roughly 30 to 100 m. None of the stations located east of 80° W had samples belonging to this regime. Mixing of Atlantic water, entering the Arctic via the Beaufort Sea, and Pacific water, primarily found in the deepest waters of the westernmost stations, (i.e. west of 100° W), displays the least amount of scatter about the proposed idealized “mixing line”. DIC data at $S > 36$, taken from a model simulation of Gulf Stream water (Thomas et al., 2008), though not plotted here, was used to validate the slope of this proposed line.

The fourth mixing regime has Atlantic source water of slightly lower salinity and higher DIC than the Atlantic-Pacific mixing end member. This is Atlantic water from the West Greenland Current in the Labrador Sea. The second end member for this mixing is a water mass which is here referred to as “diluted Pacific water”. It has lower salinity and DIC than the Pacific water, the result of mixing of river runoff and Arctic waters.

Salinity, DIC, and total alkalinity (TA) data from the Labrador Sea in 1998 (Jones, 1998) were used to identify Atlantic water from the WGC. These data were corrected for the increased atmospheric, and subsequently oceanic, CO₂ concentration over the 10 year period since the data was collected. DIC and TA data from the 1998 Labrador Sea data set were used to compute $p\text{CO}_2$ (Millero, 1994), which was then scaled up according to an increase of 1.7 ppm per year. Assuming that TA remained constant over this 10 year period, TA and the augmented $p\text{CO}_2$ values were then used to compute the present day DIC concentrations.

The water masses observed at stations in Lancaster and Jones Sounds are the result of mixing between the diluted Pacific and Atlantic water masses, with the Atlantic component seen at these locations composed of WGC water from the Labrador Sea. Mixing of diluted Pacific water with Atlantic water occurs in the depth range of roughly 80 to 200 m with the mixing of deeper waters (from 200–500 m) occurring between the diluted Pacific and Labrador Sea water masses (shown in red in Fig. 4). WGC water from Baffin Bay enters Jones and Lancaster Sounds, encounters the sill and is

returned to Baffin Bay. The contribution of Atlantic water seen at stations in Jones and Lancaster Sounds has not come via the Archipelago, but from Baffin Bay. This seems to be in agreement with Jones et al. (2003) who, using nutrient ratios as water mass tracers, found no Atlantic water, of Arctic origin, in the outflow from either Lancaster or Jones Sound.

We therefore see two distinct mixing regimes of Atlantic-Pacific water, which are separated not only in terms of water mass properties but also geography. The upper water layer at Lancaster and Jones Sound flows out of the Archipelago and into Baffin Bay with mixing along the diluted Pacific-Baffin Bay waters (shown in green in Fig. 4), and between diluted Pacific-Labrador Sea waters (shown in red in Fig. 4). However, the inflow to the Archipelago from the West (via the Beaufort Sea) is dominated by mixing between deeper Atlantic and Pacific water (shown in blue).

3.3 Deep water carbon storage

If the distribution of DIC concentration of samples resulting from the mixing of Atlantic and Pacific waters was the result of conservative mixing alone, all samples should fall along the proposed “mixing line” (shown in blue in Fig. 4). The bowed structure of the DIC distribution (Figs. 2 and 4, in blue) implies that another, biological, process is at play. Further confirmation that this is indeed a biological process, is the absence of a water mass with high salinity ($S \geq 34$), and high DIC ($\text{DIC} > 2250 \mu\text{mol kg}^{-1}$), that would act to pull our samples away from the inferred mixing line, attributing this bowed structure to a physical process. Nonconservative variations in DIC are thus attributed to biology ($\Delta\text{DIC}_{\text{bio}}$), and are then the differences between the expected (DIC_{ex}) (i.e. the idealized mixing) and the observed (DIC_{obs}) values:

$$\Delta\text{DIC}_{\text{bio}} = \text{DIC}_{\text{obs}} - \text{DIC}_{\text{ex}} \quad (5)$$

Negative values of $\Delta\text{DIC}_{\text{bio}}$ correspond to inorganic carbon deficits implying that production exceeds respiration in the system. Conversely, positive values of $\Delta\text{DIC}_{\text{bio}}$ imply that respiration exceeds production and correspond to a surplus of inorganic carbon.

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The samples associated with the greatest deviation from expected DIC values were in the range of $10 \mu\text{mol kg}^{-1} < \Delta\text{DIC}_{\text{bio}} < 50 \mu\text{mol kg}^{-1}$. Integrating the $\Delta\text{DIC}_{\text{bio}}$ over the salinity range of Pacific ($S=33.1$) and Atlantic ($S=34.88$) waters yields a total carbon surplus, or respiration inventory of $5.8 \pm 0.2 \text{ mol C m}^{-2}$.

5 Further confirmation that biology is driving the increased DIC concentrations seen in our Pacific- Atlantic water masses is evident from a plot of apparent oxygen utilization (AOU) for the same discrete samples (Fig. 5). The bowed structure of our DIC signal is mirrored in the AOU distribution. As in the case of DIC, AOU is integrated over the same range of salinity, and we find a total oxygen utilization of $7.7 \pm 0.5 \text{ mol m}^{-2}$, yielding a
10 Ratio of $\text{AOU}:\text{DIC}=1.22$. If we consider a Redfield ratio of $\text{O}_2:\text{CO}_2=138:106=1.30$, our estimates of carbon surplus and oxygen utilization are quite reasonable (Millero, 2006).

Thus primary production in the archipelago results in a drawdown of carbon to the deep water. If we now assume that the residence time of Pacific (and Atlantic) water in the Arctic Ocean is approximately 10 years (Yamamoto-Kawai et al., 2008), and
15 the size of the study region in the Archipelago is roughly $1.34 \times 10^5 \text{ km}^2$, we arrive at a carbon draw down of $9.5 \pm 1.5 \times 10^{11} \text{ g C yr}^{-1}$. If we now estimate the size of the study region in the Canadian Archipelago at roughly $0.4 \pm 0.01 \times 10^6 \text{ km}^2$ we arrive at a carbon drawdown of $2.21 \pm 0.04 \times 10^9 \text{ g C yr}^{-1}$. Bulk carbon inventories such as this can provide reliable estimates of system export production (Thomas et al., 2005). The
20 estimate made here is in general agreement with the rather sparse primary production data for this region, which ranges from 25 to $50 \text{ g C m}^{-2} \text{ yr}^{-1}$, and provides a reasonable constraint on this estimate (Cota et al., 1996; Pomeroy, 1997). Using a value of primary production of roughly $34 \text{ g C m}^{-2} \text{ yr}^{-1}$, following Cota et al. (1996), for a region with similar geographic location and water column depth, our calculated carbon surplus
25 corresponds to an export production of roughly 20%.

3.4 Carbon export to the North Atlantic

The Beaufort Sea communicates directly with the Atlantic Ocean through those passages in the Arctic Archipelago that enter Baffin Bay. Lancaster Sound, Nares Strait

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and Jones Sound all exit the Archipelago to Baffin Bay. Having identified the composition of water flowing out of the Canadian Archipelago, in this case via Jones and Lancaster Sound, we now estimate the carbon transport from the Arctic into this region. We find that water entering Baffin Bay from Jones Sound is composed of roughly 27% Arctic, 40% Pacific and 33% Atlantic water, while water from Lancaster Sound is composed of roughly 15% Arctic, 42% Pacific and 43% Atlantic water (Fig. 6, Table 2). The contribution from river runoff at both locations was found to be negligible for the purposes of the present discussion.

Several estimates of volume transport from the Archipelago, from Jones and Lancaster Sound have been made (Rudels, 1986; Ingram et al., 2002; Jones et al., 2003; Cuny et al., 2005; Prinsenberg and Hamilton, 2005). We applied the estimate of Ingram et al. (2002), which assumes that the net Eastward outflow from Jones Sound and Lancaster Sound are $0.3 \times 10^6 \text{ m}^{-3} \text{ s}^{-1}$, and $1.1 \times 10^6 \text{ m}^{-3} \text{ s}^{-1}$, respectively. Multiplying this volume transport by the average DIC concentration in a specified depth range gives an estimated value of carbon exported from the Archipelago to Baffin Bay at each location. The resulting export of carbon from Jones Sound to Baffin Bay is roughly $0.77 \times 10^{14} \text{ g C yr}^{-1}$, while that from Lancaster Sound is roughly $2.31 \times 10^{14} \text{ g C yr}^{-1}$ (Table 2). The total transport by the Baffin Current has been estimated as $1.7 \times 10^6 \text{ m}^{-3} \text{ s}^{-1}$, the outflow from Jones Sound and Lancaster Sound then supply roughly 18% and 65% of this water, respectively, making the Arctic Archipelago an important source of both water and carbon to Baffin Bay and subsequently to the North Atlantic.

An alternate approach is to compare the DIC concentration of water coming into Baffin Bay via the West Greenland current with that of the outflow from the Archipelago. In this way we can estimate the carbon enrichment resulting from the outflow of Arctic and Pacific waters via the Archipelago. We assume that the North-easternmost station of the Labrador Sea transect (Fig. 1) is representative of WGC water with a mean DIC concentration of $2130 \mu\text{mol kg}^{-1}$. Ignoring the contribution from the Hudson Strait outflow, the outflow from the Archipelago via Jones and Lancaster Sounds has a DIC

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



concentration of $2148 \mu\text{mol kg}^{-1}$ (Table 2). The difference between these values allows us to estimate the carbon enrichment at roughly $18 \mu\text{mol kg}^{-1}$, or 0.22 g C m^{-3} .

4 Conclusions

Previous studies have relied on nutrient relationships for water mass identification in the Arctic Ocean (Anderson et al., 1994; Jones et al., 1998, 2003; McLaughlin et al., 2004). We relied instead on measurements of dissolved inorganic carbon, and found it to be a useful parameter in the identification of water masses and conservative mixing relationships. Four water masses were found to dominate the water column in the Canadian Archipelago, with conservative mixing occurring between them. We were able to isolate deeper Pacific and Atlantic water entering the Arctic Ocean from the western side via the Beaufort Sea, from Pacific and water flowing eastward out of the Archipelago, and Atlantic water from the Labrador Sea encountering this outflow.

An estimate of carbon transfer from the surface waters to the deep sea was made by computing the difference between observed DIC concentrations and those expected from conservative mixing alone. An estimate of oxygen utilization produces the expected Redfield ratio with exported carbon. The carbon export to Baffin Bay via Jones sound was also estimated and found to make a significant contribution with respect to both volume transport and DIC delivery to the Baffin Current, which feeds the North Atlantic. An estimate of the carbon enrichment resulting from the outflow of Arctic and Pacific waters via the Arctic Archipelago was made.

While there remains much uncertainty with respect to carbon cycling in the Arctic, this investigation into the Canadian Archipelago sheds some light on the water mass properties in this area. Export of high carbon Pacific water to the North Atlantic has implications for the uptake of anthropogenic carbon, and hence ocean acidification in this area. However, from the perspective of natural variability, NAO driven changes in composition of waters leaving the Arctic may also influence carbon uptake in the subpolar and temperate North Atlantic. As one of the gateways from the Pacific to the

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Atlantic, the Arctic Archipelago plays an important role in the carbon chemistry of the Arctic ocean, which in turn plays a crucial role in the global carbon cycle.

Acknowledgements. This research is part of the Canadian IPY initiatives and the Circumpolar Flaw Lead System (CFL) Study. The authors are grateful for the enthusiastic co-operation of the crew of the CCGS Amundsen. We wish to thank Al Mucci for his insight and contribution to the field program. This work contributes to IGBP/IHDP LOICZ.

References

- Anderson, L. G., Björk, G., Holby, O., Jones, E. P., Kattner, G., Koltermann, K. P., Liljeblad, B., Lindergren, R., Rudels, B., and Swift, J.: Water masses and circulation in the Eurasian Basin: Results from the Oden 91 Expedition, *J. Geophys. Res.*, 99, 3273–3283, 1994.
- Anderson, L. G., Olsson, K., and Chierici, M.: A carbon budget for the Arctic Ocean, *Glob. Biogeochem. Cy.*, 12, 455–465, 1998a.
- Anderson, L. G., Olsson, K., Jones, E. P., Chierici, M., and Fransson, A.: Anthropogenic carbon dioxide in the Arctic Ocean: Inventory and sinks, *J. Geophys. Res.*, 103, 27 707–27 716, 1998b.
- Anderson, L. G., Jutterström, S., Kaltin, S., Jones, E. P., and Björk, G.: Variability in river runoff distribution in the Eurasian Basin of the Arctic Ocean, *J. Geophys. Res.*, 109, C01016, doi:10.1029/2003JC001773, 2004.
- Bates, N. R., Best, M. H. P., and Hansell, D. A.: Spatio-temporal distribution of dissolved inorganic carbon and net community production in the Chukchi and Beaufort Seas, *Deep-Sea Res. Pt. II*, 52, 3303–3323, 2005.
- Cota, G. F., Pomeroy, L. R., Harrison, W. G., Jones, E. P., Peters Jr., F., W. M. S., and Weingartner, T. R.: Nutrients, primary production and microbial heterotrophy in the southeastern Chukchi Sea: Arctic summer nutrient depletion and heterotrophy, *Mar. Ecol.-Prog. Ser.*, 135, 247–258, 1996.
- Cuny, J., Rhines, P. B., and Kwok, R.: Davis Strait volume, freshwater and heat fluxes, *Deep-Sea Res. Pt. I*, 52, 519–542, 2005.
- Ekwurzel, B., Schollosser, P., Mortlock, R. A., Fairbanks, R. G., and Swift, J. H.: River runoff, sea ice meltwater, and Pacific water distribution and mean residence times in the Arctic Ocean, *J. Geophys. Res.*, 106, 9075–9092, 2001.

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Fransson, A., Chierici, M., Anderson, L. G., Bussmann, I., Kattner, G., Jones, E. P., and Swift, J. H.: The importance of shelf processes for the modification of chemical constituents in the waters of the Eurasian Arctic Ocean: implication for carbon fluxes, *Cont. Shelf Res.*, 21, 225–242, 2001.
- 5 Friis, K., Körtzinger, A., and Wallace, D. W. R.: The salinity normalization of marine inorganic carbon chemistry data, *Geophys. Res. Lett.*, 30, 1085, doi:10.1029/2002GL015898, 2003. 976
- Greene, C. H. and Pershing, A. J.: Climate drives sea change, *Science*, 315, 1084–1085, 2007.
- 10 Hansell, D. A., Kadko, D., and Bates, N. R.: Degradation of terrigenous dissolved organic carbon in the Western Arctic Ocean, *Science*, 304, 858–861, 2004. 975
- Ingram, R. G., Bâcle, J., Barber, D. G., Gratton, Y., and Melling, H.: An overview of physical processes in the North water, *Deep-Sea Res. Pt. II*, 49, 4893–4906, 2002. 981
- Johnson, K. M., Wills, K. D., Butler, D. B., Johnson, W. K., and Wong, C. S.: Coulometric total carbon dioxide analysis for marine studies: maximizing the performance of an automated gas extraction system and coulometric detector, *Mar. Chem.*, 44, 167–188, 1993.
- 15 Jones, E. P., Anderson, L. G., and Swift, J. H.: Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: implications for circulation, *Geophys. Res. Lett.*, 25, 765–768, 1998.
- Jones, E. P., Swift, J. H., Anderson, L. G., Lipizer, M., Civitarese, G., Falkner, K. K., Kattner, G., and McLaughlin, F.: Tracing Pacific water in the North Atlantic Ocean, *J. Geophys. Res.*, 20 108, 3116, doi:10.1029/2001JC001141, 2003. 979
- Jones, P.: Total CO₂ and total alkalinity data obtained during the R/V Hudson mission in the North Atlantic Ocean during WOCE section AR01W (AR07W) (22 June–9 July, 1998), Tech. rep., Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998. 978
- 25 Kwok, R.: Recent changes in Arctic Ocean Sea ice motion associated with the North Atlantic oscillation, *Geophys. Res. Lett.*, 27, 775–778, 2000.
- Macdonald, R. W., McLaughlin, F. A., and Carmack, E. C.: Fresh water and its sources during the SHEBA drift in the Canada Basin of the Arctic Ocean, *Deep-Sea Res. Pt. I*, 49, 1769–1785, 2002. 973, 975
- 30 McLaughlin, F. A., Carmack, E. C., Macdonald, R. W., Melling, H., Swift, J. H., Wheeler, P. A., Sherr, B. F., and Sherr, E. B.: The joint roles of Pacific and Atlantic-origin waters in the Canada Basin, 1997–1998, *Deep-Sea Res. Pt. I*, 51, 107–128, 2004. 975

BGD

6, 971–994, 2009

Carbon cycling in the Arctic ArchipelagoE. H. Shadwick et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Carbon cycling in the Arctic ArchipelagoE. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Miller, L. A., Yager, P. L., Erickson, K. A., Amiel, D., Bâcle, J., Cochran, J. K., Garneau, M.-E., Gosselin, M., Hirschberg, D. J., Klein, B., LeBlanc, B., and Miller, W. L.: Carbon distributions and fluxes in the North Water, 1998 and 1999, *Deep-Sea Res. Pt. II*, 49, 5151–5170, 2002.
- 5 Millero, F. J.: Thermodynamics of the carbon dioxide system in the oceans, *Geochim. Cosmochim. Ac.*, 59, 661–677, 1994. 978
- Millero, F. J.: *Chemical oceanography*, Taylor & Francis, 2006. 980
- Peterson, B., Holmes, R. M., McClelland, J., Vorosmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., and Rahmstorf, S.: Increasing river discharge to the Arctic Ocean, *Science*, 298, 2171–2173, 2002.
- 10 Peterson, B., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E., and Aagaard, K.: Trajectory shifts in the Arctic and Subarctic freshwater cycle, *Science*, 313, 1061–1066, 2006.
- Pomeroy, L. R.: Primary production in the Arctic Ocean estimated from dissolved oxygen, *J. Marine Syst.*, 10, 1–8, 1997.
- Prinsenber, S. and Hamilton, J.: Monitoring the volume, freshwater and heat fluxes passing through Lancaster Sound in the Canadian Arctic Archipelago, *Atmos. Ocean*, 43, 1–22, 2005.
- 15 Rahmstorf, S.: Ocean circulation and climate during the past 120 000 years, *Nature*, 419, 207–214, 2002. 973
- Robbins, P. E.: Oceanic carbon transport carried by freshwater divergence: Are salinity normalizations useful?, *J. Geophys. Res.*, 106, 30 939–30 946, 2001.
- 20 Rudels, B.: The outflow of polar water through the Arctic Archipelago and the oceanographic conditions in Baffin Bay, *Polar Res.*, 4, 161–180, 1986.
- Serreze, M. C., Barrett, A. P., Slater, A. G., Woodgate, R. A., Aagaard, K., Lammers, R. B., Steele, M., Moritz, R., Meredith, M., and Lee, C. M.: The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, 111, C11010, doi:10.1029/2005JC003424, 2006. 973
- 25 Smith, W. O. and Gordon, L. L.: Hyperproductivity of the Ross Sea (Antarctica) polynya during austral spring, *Geophys. Res. Lett.*, 24, 233–236, 1997.
- Steele, M. and Boyd, T.: Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, 103, 10 419–10 435, 1998.
- 30 Thomas, H., Bozec, Y., Elkalay, K., de Baar, H. J. W., Borges, A. V., and Schiettecatte, L.-S.: Controls of the surface water partial pressure of CO₂ in the North Sea, *Biogeosciences*, 2, 323–334, 2005, <http://www.biogeosciences.net/2/323/2005/>. 980

- Thomas, H., Prowe, F., Lima, I. D., Doney, S. C., Wanninkhof, R., Greatbatch, R. J., Schuster, U., and Corbiere, A.: Changes in the North Atlantic Oscillation influence CO₂ uptake in the North Atlantic over the past 2 decades, *Glob. Biogeochem. Cy.*, 22, GB4027, doi:10.1029/2007GB003167, 2008. 973, 978
- 5 Thompson, D. W. and Wallace, J. M.: Regional Climate Impacts of the Northern Hemisphere Annular Mode, *Science*, 293, 85–89, 2001. 973
- Yamamoto-Kawai, M. and Tanaka, N.: Freshwater and brine behaviors in the Arctic Ocean deduced from historical data of $\delta^{18}\text{O}$ and alkalinity (1992–2002 A.D.), *J. Geophys. Res.*, 110, C10003, doi:10.1029/2004JC002793, 2005. 975
- 10 Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., and Shimada, K.: Freshwater budget of the Canada Basin, Arctic Ocean, from salinity, $\delta^{18}\text{O}$ and nutrients, *J. Geophys. Res.*, 113, C01007, doi:10.1029/2006JC003858, 2008.

BGD

6, 971–994, 2009

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Table 1. End member properties used in the two and three component mass balance equations.

| Water Mass | Salinity | DIC $\mu\text{mol kg}^{-1}$ | DIC _{norm} $\mu\text{mol kg}^{-1}$ |
|--------------|----------|-----------------------------|---|
| River Runoff | 0 | 320 | 2892 |
| Arctic | 29.87 | 1934 | 2104 |
| Pacific | 33.1 | 2236 | 2204 |
| Atlantic | 34.88 | 2154 | 2007 |

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

Table 2. Water mass composition for flow out of the Arctic Archipelago into Baffin Bay via Jones Sound (top), and Lancaster Sound (bottom) where volume transport is given in $\times 10^6 \text{ m}^3 \text{ s}^{-1}$, and the total carbon transport in units of $\times 10^{14} \text{ g C yr}^{-1}$. DIC is given in units of $\mu\text{mol kg}^{-1}$, and f_{xxx} , and T_{xxx} , are the water mass fraction and corresponding carbon transport for Arctic (arc), Pacific (pac), and Atlantic (atl) water. The volume and carbon transport from both Jones and Lancaster Sounds are given in the last row.

| Depth | Volume Transport | DIC | Carbon Transport | f_{arc} | T_{arc} | f_{pac} | T_{pac} | f_{atl} | T_{atl} |
|---------|------------------|------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 0–30 | 0.03 | 1957 | 0.23 | 0.92 | 0.22 | 0.08 | 0.02 | 0 | 0 |
| 30–150 | 0.12 | 2121 | 0.99 | 0.32 | 0.32 | 0.30 | 0.30 | 0.38 | 0.38 |
| 150–200 | 0.05 | 2154 | 0.42 | 0.18 | 0.07 | 0.40 | 0.17 | 0.42 | 0.18 |
| 200–300 | 0.1 | 2172 | 0.84 | 0.05 | 0.04 | 0.63 | 0.53 | 0.32 | 0.27 |
| Total | 0.3 | 2127 | 0.77 | 0.27 | 0.21 | 0.40 | 0.31 | 0.33 | 0.26 |
| 0–30 | 0.066 | 1970 | 0.51 | 0.9 | 0.45 | 0.02 | 0.010 | 0.08 | 0.04 |
| 30–120 | 0.198 | 2125 | 1.63 | 0.31 | 0.51 | 0.28 | 0.46 | 0.41 | 0.67 |
| 120–150 | 0.066 | 2151 | 0.55 | 0.20 | 0.11 | 0.36 | 0.20 | 0.44 | 0.24 |
| 150–200 | 0.11 | 2154 | 0.92 | 0.16 | 0.17 | 0.47 | 0.43 | 0.37 | 0.34 |
| 200–300 | 0.22 | 2174 | 1.86 | 0.06 | 0.11 | 0.60 | 1.11 | 0.34 | 0.63 |
| 300–500 | 0.44 | 2185 | 3.73 | 0 | 0 | 0.46 | 1.72 | 0.54 | 2.02 |
| Total | 1.1 | 2154 | 2.31 | 0.15 | 0.35 | 0.42 | 0.98 | 0.43 | 0.99 |
| Both | 1.4 | 2148 | 3.08 | | | | | | |

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

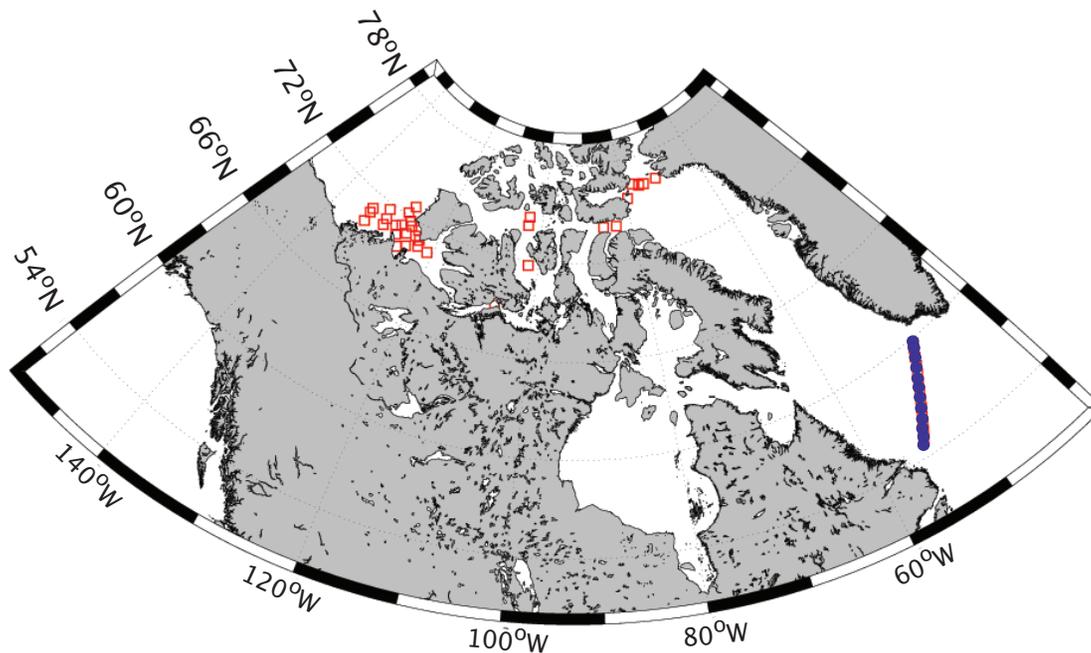


Fig. 1. Locations of stations sampled for dissolved inorganic carbon (DIC) and hydrographic data. Red squares indicate stations occupied in 2007, blue circles indicate stations from which an older data set from the Labrador Sea was used.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

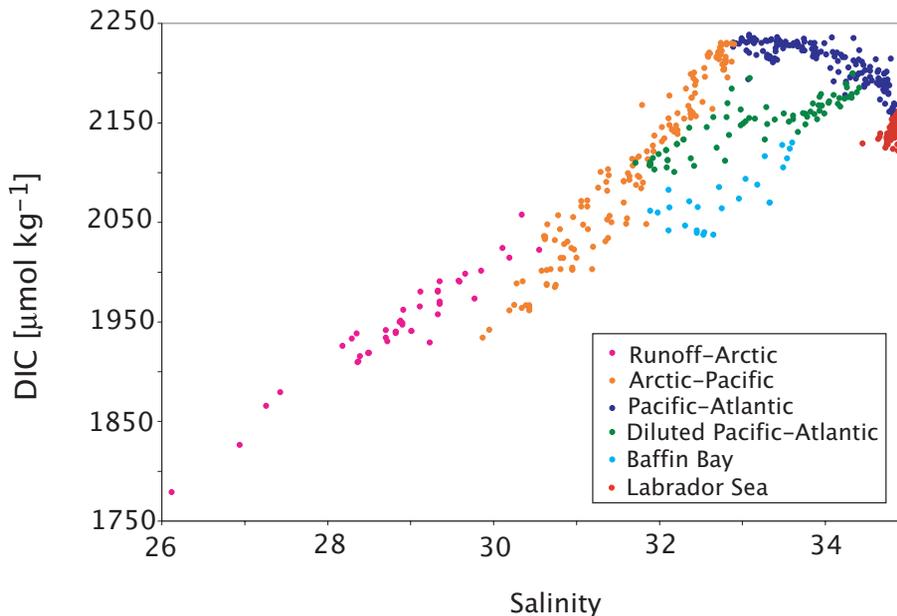


Fig. 2. Dissolved inorganic carbon (DIC) versus salinity for samples taken at all stations identified by the red squares in Fig. 1. Four water masses are indicated: fresh-Arctic (pink), Arctic-Pacific (orange), Pacific-Atlantic (blue), and diluted Pacific-Atlantic (green). Surface water samples from stations located in Baffin Bay are plotted in pale blue. Samples from the Labrador Sea (in part via the West Greenland Current) are shown in red.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

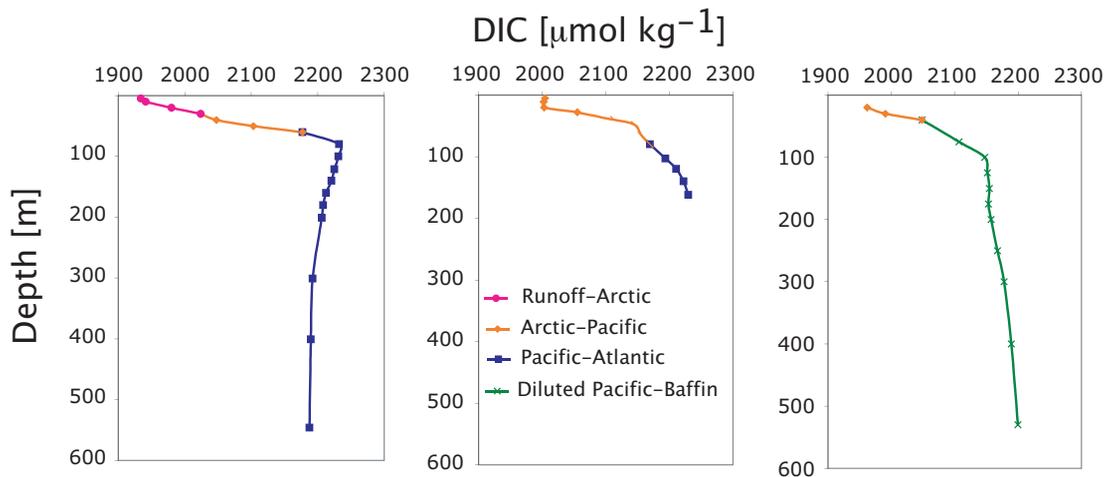


Fig. 3. Profiles of dissolved inorganic carbon (DIC) for (a) a station located west of Banks Island, (b) a station centrally located in the Canadian Archipelago, and (c) a station located near the outflow of Lancaster Sound to Baffin Bay. The coloured lines indicated the dominance of mixing between: (pink) fresh and Arctic water; (orange) Arctic and Pacific water; (blue) Pacific and deep Atlantic water coming via the Beaufort Sea, and (green) diluted Pacific and Atlantic water, coming via the Labrador Sea, respectively.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

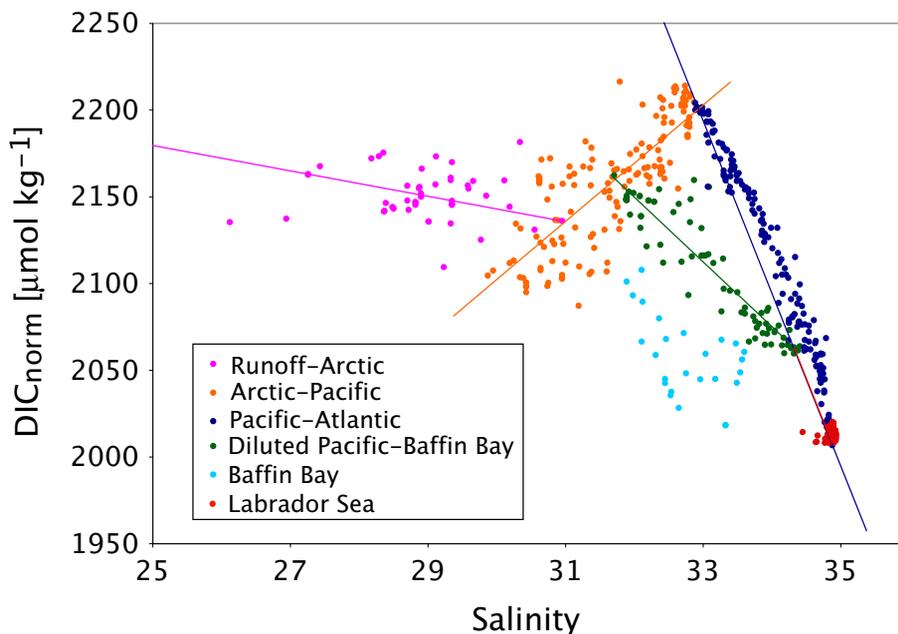


Fig. 4. Salinity normalized DIC versus salinity. Five idealized mixing lines are indicated: river runoff-Arctic (pink), Arctic-Pacific (orange), Pacific-Atlantic (blue), diluted Pacific-Atlantic (green), and diluted Pacific-Labrador Sea (red). Surface water samples from stations located in Baffin Bay are plotted in pale blue. These samples do not result from mixing between diluted Pacific and Atlantic water (green), or between Atlantic and Pacific water (blue). These water masses rather result from a contribution from sea-ice melt which adds fresh water, without changing the DIC concentration, thereby shifting the points horizontally, away from the inferred (idealized) mixing lines.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

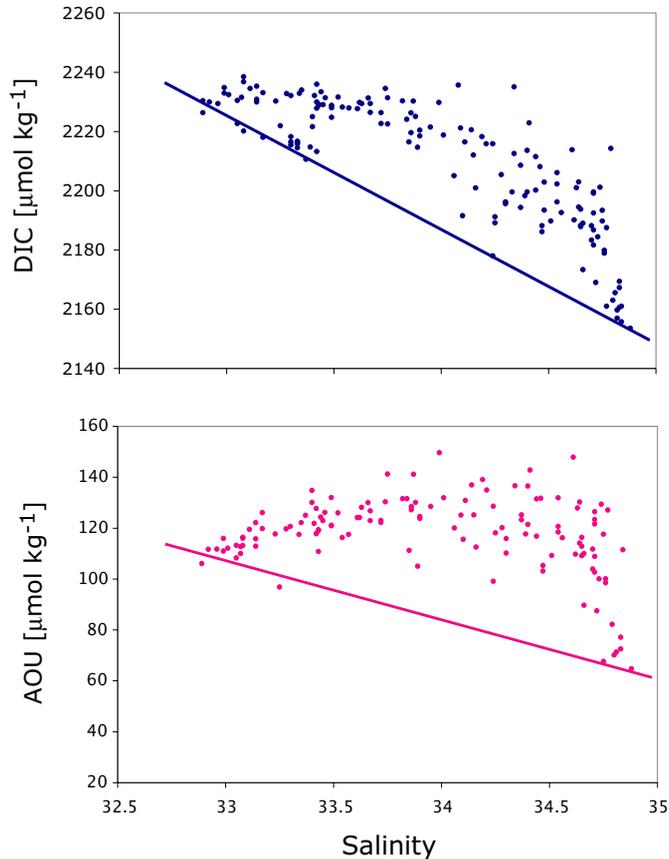


Fig. 5. Water masses of Pacific and Atlantic origin, from the Beaufort sea are plotted in blue, while the corresponding AOU is plotted in pink over the same salinity range. Integrating $\Delta\text{DIC}_{\text{bio}}$, and AOU over the salinity range of Pacific ($S=33.1$) and Atlantic ($S=34.88$) waters yields a total carbon surplus, or respiration inventory, of $5.8 \pm 0.2 \text{ mol C m}^{-2}$, and a corresponding oxygen utilization of $7.7 \pm 0.5 \text{ mol Oxygen m}^{-2}$.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Carbon cycling in the Arctic Archipelago

E. H. Shadwick et al.

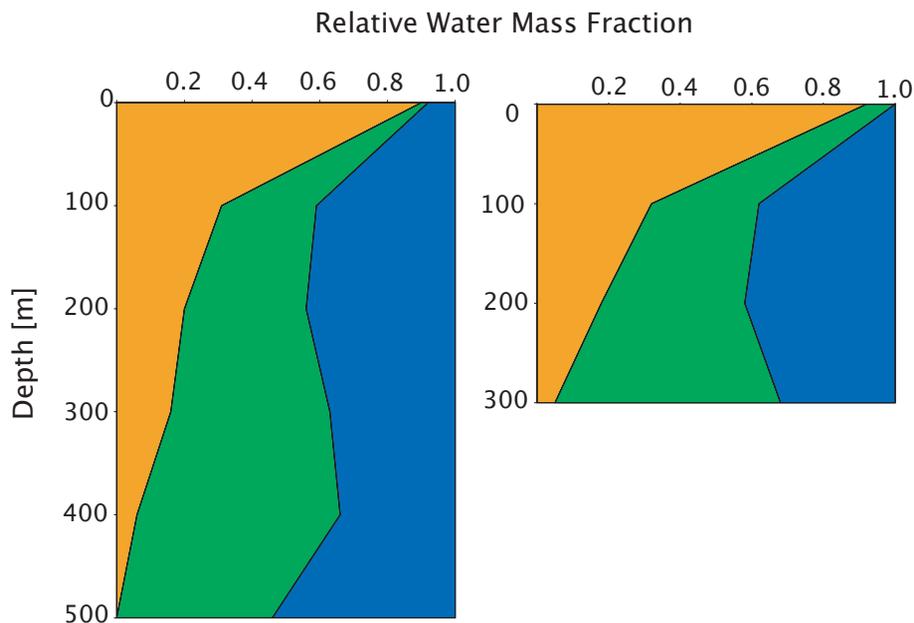


Fig. 6. The relative contributions of Arctic (orange), Pacific (green), and Atlantic (blue) water to the water column at Lancaster Sound (left) and Jones Sound (right).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

