



**HAL**  
open science

## Inorganic carbon time series at Ocean Weather Station M in the Norwegian Sea

I. Skjelvan, E. Falck, F. Rey, S. B. Kringstad

► **To cite this version:**

I. Skjelvan, E. Falck, F. Rey, S. B. Kringstad. Inorganic carbon time series at Ocean Weather Station M in the Norwegian Sea. *Biogeosciences Discussions*, 2007, 4 (4), pp.2929-2958. hal-00297915

**HAL Id: hal-00297915**

**<https://hal.science/hal-00297915>**

Submitted on 18 Jun 2008

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

**Inorganic carbon  
time series**

I. Skjelvan et al.

# Inorganic carbon time series at Ocean Weather Station M in the Norwegian Sea

I. Skjelvan<sup>1,2</sup>, E. Falck<sup>2</sup>, F. Rey<sup>3</sup>, and S. B. Kringstad<sup>2,1</sup>

<sup>1</sup>Bjerknes Centre for Climate Research, University of Bergen, Norway

<sup>2</sup>Geophysical Institute, University of Bergen, Norway

<sup>3</sup>Institute of Marine Research, Bergen, Norway

Received: 15 August 2007 – Accepted: 23 August 2007 – Published: 27 August 2007

Correspondence to: I. Skjelvan (ingunn.skjelvan@gfi.uib.no)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

## Abstract

Dissolved inorganic carbon ( $C_T$ ) has been collected at Ocean Weather Station M (OWSM) in the Norwegian Sea since 2001. Seasonal variations in  $C_T$  are confined to the upper 50 m, where the biology is active, and below this layer no clear seasonal signal is seen. From winter to summer the surface  $C_T$  concentration typical drops from 2140 to about 2040  $\mu\text{mol kg}^{-1}$ , while a deep water  $C_T$  concentration of about 2163  $\mu\text{mol kg}^{-1}$  is measured throughout the year. Observations show an annual increase in salinity normalized carbon concentration ( $nC_T$ ) of  $1.3 \pm 0.7 \mu\text{mol kg}^{-1}$  in the surface layer, which is equivalent to a  $\text{pCO}_2$  increase of  $2.6 \pm 1.2 \mu\text{atm yr}^{-1}$ , i.e. larger than the atmospheric increase in this area. Observations also show an annual increase in the deep water  $nC_T$  of  $0.57 \pm 0.24 \mu\text{mol kg}^{-1}$ , of which about a tenth is due to inflow of old Arctic water with larger amounts of remineralised matter. The remaining part has an anthropogenic origin and sources for this might be Greenland Sea surface water, Iceland Sea surface water, and/or recirculated Atlantic Water. By using an extended multi linear regression method (eMLR) it is verified that anthropogenic carbon has entered the whole water column at OWSM.

## 1 Introduction

The ocean is one of several reservoirs indirectly controlling the climate system through exchange of  $\text{CO}_2$  with the atmosphere. Human activities, such as burning of fossil fuels and deforestation, release annually an anthropogenic carbon amount of about  $7.2 \times 10^{15}$  g C into the atmosphere, and of this, about one third is taken up by the world oceans (IPCC, 2007). The North Atlantic is known to store relatively large amounts of anthropogenic carbon, which has been captured through formation of intermediate and deep waters in subpolar areas (Friis et al., 2005). It is, however, not straight forward to quantify this amount, due to a lack of oceanic reference data from the pre-industrial times, and indirect methods have to be used (e.g. Wallace, 1995; Gruber et al., 1996).

**BGD**

4, 2929–2958, 2007

## Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

In particular, the Nordic Seas in the northern North Atlantic is described as an important sink region for atmospheric CO<sub>2</sub> (e.g. Takahashi et al., 2002; Skjelvan et al., 2005), however, recent research suggests that the size of this sink seems to be regionally decreasing, based on an observed seawater fCO<sub>2</sub> which annually increases faster than the atmospheric fCO<sub>2</sub> (Olsen et al., 2006). Carbon time series data from this area are, in this respect, valuable contributions to evaluate the development of the oceanic carbon uptake.

The Ocean Weather Station M (OWSM) is situated in the western branch of the Norwegian Atlantic Current, at 66° N; 2° E, over the Norwegian continental slope (Fig. 1). The station, which has a depth of about 2100 m, was started in 1948 and is today operated by M/S *Polarfront*; the last weather ship in the world. Temperature and salinity have been measured from the very beginning (e.g. Østerhus and Gammelsrød, 1999; Nilsen and Falck, 2006), closely followed by dissolved oxygen (Nilsen and Falck, 2006; Kivimäe and Falck, 2007<sup>1</sup>). In the 1980s analyses of atmospheric CO<sub>2</sub> content were started (Tans and Conway, 2005), and since 1990 nutrients have been determined weekly (Dale et al., 1999). During a four years period and on a monthly basis in the early 1990s, total dissolved inorganic carbon (C<sub>T</sub>) was determined for the very first time at OWSM, using gas extraction of acidified water samples and manometric detection (Gislefoss et al., 1998), however, these are not used in the following due to insufficient precision (±12 μmol kg<sup>-1</sup>). Since November 2001 monthly measurements of C<sub>T</sub> and alkalinity has been performed using modern analyzing techniques.

Warm and saline Atlantic Water from the Norwegian Atlantic Current occupies the upper layer at OWSM down to 300–400 m, with present temperatures typically varying between 7°C in the winter and 12°C in the summer time. Cold and less saline deep water occupies the water column from about 1000 m down to the bottom (Norwegian Sea Deep Water), and in between these two water masses there is a layer of interme-

<sup>1</sup>Kivimäe, C. and Falck, E.: Interannual variability of net community production at Ocean Weather Station M in the Norwegian Sea during 51 years, *Global Biogeochem. Cycles*, submitted, 2007.

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

diate water; Arctic Intermediate Water, of fluctuating thickness. At times with northerly or north-easterly winds during summer, the fresher Norwegian Coastal Water is driven away from the coast and will occasionally reach all the way out to OWSM. We refer to Nilsen and Falck (2006) for a more thorough description of the hydrographic conditions in the OWSM area.

In this paper we present the new  $C_7$  time series data from OWSM in the Norwegian Sea since fall 2001. We describe the seasonal and interannual variations, and we use the multiple linear regression (MLR) method of Wallace (1995) in an extended version formalized by Friis et al. (2005); eMLR; to determine the anthropogenic  $\text{CO}_2$  increase in this area of the Nordic Seas during the last two decades since the Transient Tracers in the Ocean, North Atlantic Study (TTO-NAS) expedition in 1981.

## 2 Data

At present, hydrographic measurements at OWSM are performed using a Sea-Bird CTD (SBE 37-SM MicroCAT with conductivity, temperature, and pressure sensors), which is calibrated towards bottle salinity samples. Nansen bottles, with reversing thermometers, are used to collect samples for inorganic carbon, dissolved oxygen, nutrients, and salinity at standard depths. Samples for  $C_7$  are conserved with 0.02%, by volume, of saturated  $\text{HgCl}_2$  solution and analysed ashore in general within a month, however, a few samples have been stored for up to six months when the analytical instruments have been occupied at cruises.  $C_7$  is determined by gas extraction of acidified water samples and further coulometric titration (DOE, 1994; Johnson et al., 1993), and accuracy is set by running CRM supplied by Andrew Dickson of Scripps Institution of Oceanography. The precision has been determined to  $\pm 0.5 \mu\text{mol kg}^{-1}$  based on 10 duplicate samples. A comparison of the Norwegian Sea Deep Water, year by year, resulted in a standard deviation of  $\pm 1.5 \mu\text{mol kg}^{-1}$ ; however, this most likely has other sources than imprecision in the measurements. Dissolved oxygen is measured on board using the Winkler titration method with visual detection of the

**BGD**

4, 2929–2958, 2007

### Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

titration end point, and this in general gives a precision of 1%. Nutrients are conserved using chloroform and kept at 4°C until analysis ashore within six weeks after sampling. The analyses were made using standard methods on a Skalar Auto Analyzer until 2003 and an Alpkem Auto Analyzer since then. Precision for nitrate, phosphate, and silicate are 3%, 4%, and 2%, respectively. The salinity samples are analyzed ashore within a month after sampling using PorterSal salinometer with a precision of 0.003. Due to technical problems there is a gap in the time series from April to October 2004, i.e. no water samples were collected during this period.

The TTO-NAS ran from April to October 1981 and consisted of 7 legs. In the present study we have used data from leg 5, which was carried out during July and August 1981 in the Nordic Seas, and the precision of these data is reported to be  $\pm 3.7 \mu\text{mol kg}^{-1}$ . The data are obtained from the Carbon Dioxide Information Analysis Center (Oak Ridge, Tennessee, USA) and are thoroughly described in e.g. Olsen et al. (2006). Tanhua and Wallace (2005) reanalyzed TTO data from legs 2, 3, 4, and 7, and compared them with modern data adjusted to CRMs. Based on this they recommended that the TTO alkalinity data should be reduced by  $3.4 \mu\text{mol kg}^{-1}$ , and that the TTO  $C_T$  data should be recalculated using adjusted alkalinity data and further increased by  $2.4 \mu\text{mol kg}^{-1}$ . This correction has also been performed on the data from leg 5.

### 3 Seasonal and interannual variability

The inorganic carbon content of the seawater in this area varies at different time scales. The upper water mass at OWSM experiences seasonal changes due to physical, chemical, and biological processes. A clear seasonality is, for instance, seen in the upper layer temperature with warming during the summer seasons and cooling during winters (Fig. 2). The depth of the mixed layer at OWSM varies in general between 20 m in summer to 300–400 m in winter (Nilsen and Falck, 2006) and below the winter mixed layer no clear seasonal signal is seen (Fig. 2). However, the depth of the transition layer between the Atlantic Water and the intermediate water at OWSM is known

**BGD**

4, 2929–2958, 2007

## Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

to fluctuate considerably (e.g. Mosby, 1962) and this can clearly be seen in Fig. 2 at depths between 300 and 600 m, where the period of the temperature fluctuations is disconnected with the season. Below about 700 m the temperature decreases toward the bottom from 0 to about  $-0.83^{\circ}\text{C}$ .

5 Figure 3 shows all the  $C_T$ , nitrate, and silicate data from 2001 to 2006, and Fig. 4 shows  $C_T$ , nitrate, silicate, temperature, and salinity at different depth layers from 2001 to 2006. The highest variability for all parameters is seen in the surface layer, and this is closely linked to the biological activity starting in the spring and extending into the summer season. The phytoplankton growth starts in April-May as a combined result  
10 of increased solar radiation, shallowing of the mixed layer, and the establishment of a seasonal pycnocline (Rey, 2004). With the onset of the primary production the concentrations of  $C_T$  and nutrients decrease in the surface layer. This depletion continues until mid or late summer, when respiration and remineralisation take over as dominating processes controlling the  $C_T$  and nutrients concentrations.

15 At 50 m depth there is a temporary decrease in  $C_T$ , nitrate, and silicate concentrations just after the onset of primary production, when the mixed layer is still deeper than 50 m. The major depletion at this depth appears to occur in September-October (Figs. 4a, b, and c), when the surface water low in  $C_T$  and nutrients is mixed downwards due to wind mixing and vertical convection achieved by cooling of the surface (Fig. 4d).  
20 As the mixed layer depth increases further the carbon and nutrient rich waters from depths below 50 m are mixed upwards in the water column and reintroduced into the surface layer, increasing the surface concentrations towards winter values.

25 The biological drawdown during spring and summer is confined to the upper 50 m and below 100 m there is no clear seasonal signal in  $C_T$  and nutrients. From winter to summer the surface  $C_T$ , nitrate, and silicate decrease by about 100, 11, and  $4\ \mu\text{mol kg}^{-1}$ , respectively (Figs. 4a, b, and c). The lowest  $C_T$  concentrations are found in August, while the nutrients have their lowest concentrations in July.

While there is an indisputable difference between summer and winter values in upper waters, no clear seasonal signal is seen in the deeper layers. In the transition zone

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

between the Atlantic Water and the Arctic Intermediate Water (300–600 m; Fig. 3a) the  $C_T$  concentration increases from about 2140 to about 2165  $\mu\text{mol kg}^{-1}$ . In the core of the intermediate water, between about 500 and 1000 m, there is a small  $C_T$  maximum (Fig. 3a), and below this the concentration is slightly decreasing towards the bottom.

5 For nitrate (Fig. 3b), the increase in the transition layer is 2  $\mu\text{mol kg}^{-1}$ , with a small further increase of 1  $\mu\text{mol kg}^{-1}$  in the deep water. The silicate concentration (Fig. 3c) increases from about 6 to about 9  $\mu\text{mol kg}^{-1}$  in the transition zone, and increases further towards the bottom. At 2000 m depth  $C_T$ , nitrate, and silicate values are about 2163, 15, and 12  $\mu\text{mol kg}^{-1}$ , respectively, throughout the year. Typical values for the  
10 different parameters at different depth layers and seasons are presented in Table 1, however, deviations from these are certainly observed.

When it comes to interannual variations, the degree of carbon depletion in the mixed layer during summer seasons do vary from year to year; a feature which is also seen in the silicate, but not in the nitrate (Figs. 4a, b, and c). During 2005 the concentration  
15 of  $C_T$  dropped by about 80  $\mu\text{mol kg}^{-1}$  from winter to summer compared to a  $C_T$  drop of about 100  $\mu\text{mol kg}^{-1}$  from winter to summer in previous years. A similar picture is seen for the salinity normalized  $C_T$  ( $nC_T = C_T \cdot S / 35.1$ ; not shown), which indicates that this feature is not caused by a change in salinity. The feature is mainly explained by a colder surface temperature during summer 2005 compared to the previous summers  
20 (see Figs. 2 and 4d). During 2005 the surface temperature was about 2°C colder than previous years, and this corresponds to a  $C_T$  increase of about 16  $\mu\text{mol kg}^{-1}$  (Lewis and Wallace, 1998). Also surface silicate values were less depleted during summer 2005 and 2006 compared to previous summers. The reason for this might be connected to sub-optimal diatom growth or to heavy grazing on diatoms resulting in a  
25 lower phytoplankton biomass (Rey, 2004).

To determine any interannual trend in the inorganic carbon content of the surface water the winter surface (10 m)  $nC_T$  concentration during the years 2002 to 2006 is plotted in Fig. 5a. Winter season is defined as the months January to March, and a regression line is drawn through the points. The figure shows two things; first, within the

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

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

same winter the mixed layer in general increases from January towards March, which increases the carbon concentration in the surface layer. Second, and most interesting when it comes to variations from year to year, the slope of the regression line indicates an annual  $nC_T$  increase of  $1.3 \pm 0.7 \mu\text{mol kg}^{-1}$  (with a significance level of 92%). An annual increase of not salinity normalized  $C_T$  values of  $1.5 \pm 0.5 \mu\text{mol kg}^{-1}$  was also determined (not shown), which indicates that less than a tenth of the observed annual increase in surface  $C_T$  is due to salinity changes. The slope in  $nC_T$  is equivalent to a  $\text{pCO}_2$  increase of  $2.6 \pm 1.2 \mu\text{atm yr}^{-1}$  (at constant alkalinity of  $2320 \mu\text{mol kg}^{-1}$ ; Lewis and Wallace, 1998). The winter season was chosen to eliminate any interannual variations in primary production. To check the solidity in this interannual signal we examined the carbon content in the winter (January to March) mixed layer over the years, since the winter is the time of the year when the mixed layer is deepest and coldest (Nilsen and Falck, 2006). The mixed layer depth was determined as the depth where the  $\sigma_t$  had changed equivalent to a decrease in the surface temperature of  $0.8^\circ\text{C}$  (Kara et al., 2000). For density profiles with surface instability stronger than  $0.02 \text{ kg m}^{-3}$  the first stable value below the surface was used as the surface value. Further, the averaged salinity normalized carbon content of the mixed layer during the winter months were calculated by integrating over the mixed layer, and the result is plotted in Fig. 5b. The slope of the regression line indicates an increase in the mixed layer carbon content of  $1.2 \pm 0.9 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$  (equivalent to an annual  $\text{pCO}_2$  increase of  $2.4 \pm 1.6 \mu\text{atm}$ ; Lewis and Wallace, 1998), which is similar to what is determined for the surface water. According to Tans and Conway (2005) and T. Conway (personal communication) the annual atmospheric  $\text{CO}_2$  increase at OWSM was  $2.1 \pm 0.2 \mu\text{atm}$  for the period between 2001 and 2005, and  $1.63 \pm 0.03 \mu\text{atm}$  for the period between 1982 to 2005; i.e. less compared to the oceanic carbon increase.

A closer look into the deep water  $C_T$  (Fig. 5c) also shows an interannual signal, and at 2000 m deep the  $nC_T$  increases by  $0.57 \pm 0.24 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$  (significance level of 97%). This might be connected to the changes seen in the deep water at OWSM during the last decades (Østerhus and Gammelsrød, 1999) and will be discussed further in

Chapter 5. At 800, 1000, and 1500 m we observe annual increases in  $nC_T$  of 1.4, 0.8 and  $0.9 \mu\text{mol kg}^{-1}$ , respectively.

#### 4 Determining changes in anthropogenic carbon

During the last decade or so there have been numerous attempts to determine the anthropogenic part of the carbon exchange between the atmosphere and the ocean (e.g. Wallace, 1995; Gruber et al., 1996; Sabine et al., 1999). In this work we have used the extended multi linear regression (eMLR) method documented in Friis et al. (2005), which has its origin in the multivariate time-series method of Wallace (1995), to determine changes in the anthropogenic carbon content of the water.

The method is based upon the assumptions that the spatial  $C_T$  distribution in a given region can be described by a linear multi-parameter model and that, over the time period of the study, there are no temporal changes in the correlation between  $C_T$  and the independent parameters used in the method. In the real world,  $C_T$  is perturbed both by natural variability and anthropogenic input, but it is assumed that when predictive parameters like salinity, nutrients, AOU (apparent oxygen utilization), or alkalinity are taken into account this can adjust for the natural variations.

The rationale is to use a recent data set from one region; in this case OWSM data from 2005, and compare it with a historical data set from the same region; i.e. data from the TTO-NAS expedition in 1981.  $C_T$  values from the two time periods are predicted by using a combination of independent parameters; salinity, nitrate, silicate, and potential temperature, from the respective time periods:

$$C_{T,\text{pred}}^t = a^t + b^t S^t + c^t \text{NO}_3^t + d^t \text{SiO}_2^t + e^t \theta^t \quad (1)$$

where  $a$ ,  $b$ ,  $c$ ,  $d$ , and  $e$  are regression coefficients specific for the particular dataset, and  $t$  refers to the TTO or OWSM data. The change of anthropogenic carbon in the water column over the time span is then determined by subtracting the time specific

**BGD**

4, 2929–2958, 2007

### Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

equations from each other:

$$\Delta C_T^{\text{ant}} = (a^{t2} - a^{t1}) + (b^{t2} - b^{t1})S^{t2} + (c^{t2} - c^{t1})\text{NO}_3^{t2} + (d^{t2} - d^{t1})\text{SiO}_2^{t2} + (e^{t2} - e^{t1})\theta^{t2} \quad (2)$$

where  $t1$  and  $t2$  represents the TTO and OWSM data, respectively. A similar approach is used in Olsen et al. (2006). An advantage of the eMLR approach compared to the MLR is that the measurement error of the independent parameters is minimized since this error is included in the prediction both in the recent and the historical dataset (Friis et al., 2005).

With the view of the Norwegian Sea as a diatom dominated area, it makes sense that silicate is one of the parameters that should be included in the predictive term for  $C_T$ . On the other hand, parameters like phosphate and AOU were also considered in the regression, with not as good fit as with the present combination of parameters. The use of phosphate and AOU even resulted in  $C_T$  residuals with a biased variation with depth, which indicates that these parameters are not independent.

From the TTO-NAS, Leg 5, we have chosen 3 stations from the Nordic Seas (see Fig. 1). These data were chosen due to relatively similar hydrographical characteristics to those found at OWSM (see Fig. 6). Nitrate values lower than  $0.5 \mu\text{mol kg}^{-1}$ , which were the case for a few data points, have been excluded in both datasets to avoid situations with possible overconsumption of carbon at low nutrient levels (Falck and Anderson, 2005). The eMLR approach was applied and Table 2 presents essential outputs from the calculation, such as regression coefficients of Eq. (1) for the TTO and OWSM data and statistics. The calculated  $C_T$  residuals ( $C_{T\text{measured}} - C_{T\text{predicted}}$ ) from the two datasets were relatively homogeneously distributed around zero throughout the water column (Fig. 7), which support the choice of independent variables for the  $C_T$  prediction. The highest scatter is found in the surface layer, which is the area of high biological activity, and this expresses that the method does not fully compensate for the biology. The distribution of the  $C_T$  residuals is used to estimate the accuracy of the eMLR method, and for the upper 200 m the accuracy is set to  $\pm 7 \mu\text{mol kg}^{-1}$ , while below this the value is  $\pm 4 \mu\text{mol kg}^{-1}$ .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 8 presents the anthropogenic increase of carbon at OWSM in the Norwegian Sea over the 24 years period from 1981 to 2005. The variation in the surface layer is large; however, the overall picture is that anthropogenic carbon seems to have entered the whole water column during these 24 years. The deep layer has experienced the lowest anthropogenic carbon increase of about  $9 \pm 4 \mu\text{mol kg}^{-1}$  and the upper water mass has increased its anthropogenic carbon content of about  $25 \pm 7 \mu\text{mol kg}^{-1}$ . Olsen et al. (2006) calculated increases in anthropogenic carbon of the surface and deep waters of about  $17 \pm 10$  and  $6 \pm 5 \mu\text{mol kg}^{-1}$ , respectively, over 21.5 years at a location west of OWSM. The present study indicates that the anthropogenic carbon input might have been slightly larger than this.

The eMLR method was checked by using Eq. (2) to backward calculate the  $\Delta C_T^{\text{ant}}$ , i.e. regression constants for TTO data subtracted from regression constants for OWSM data and further multiplied with TTO data. This showed an anthropogenic carbon increase similar to Fig. 8, which confirms the solidity of the eMLR method.

OWSM data from 2006 were also tried out in the anthropogenic carbon change calculation, but due to some strange surface water results these data were not used further in the eMLR calculations.

## 5 Discussion

Until recently, the oceanic uptake of atmospheric  $\text{CO}_2$  at high latitudes has been supposed to be increasing due to a strong deep mixing (Takahashi et al., 2002). The argument has been that under such mixing conditions any oceanic signal of the increasing atmospheric  $\text{CO}_2$  content would be diluted to undetectable levels, i.e. the ocean surface would not show any detectable interannual increase of  $\text{pCO}_2$ . In the current study, which focuses on OWSM in the Norwegian Sea, the surface water carbon content is observed to increase at a slightly higher speed ( $2.6 \mu\text{atm yr}^{-1}$ ) than what is seen in the atmosphere ( $2.1 \mu\text{atm yr}^{-1}$ ) over the years 2001 to 2006, which is in concert with recent research (e.g. Olsen et al., 2006; Omar and Olsen, 2006).

**BGD**

4, 2929–2958, 2007

### Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

**Inorganic carbon  
time series**

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The consequence of this is that the oceanic uptake of atmospheric  $\text{CO}_2$  in this area is decreasing and the carbon content of the Atlantic Water seems to be moving towards equilibrium with respect to air-sea  $\text{CO}_2$  exchange; i.e. no net oceanic uptake or release of  $\text{CO}_2$ . This is intuitively in contradiction to an atmosphere with an increasing amount of  $\text{CO}_2$ . However, according to Wallace (2001) this can be explained by a reduction in the buffer capacity of the northward flowing water compared to previous times. This is a result of a reduced out-gassing at lower latitudes due to higher atmospheric  $\text{CO}_2$  levels. In this way more carbon is left in the water to be transported northwards, and when the water cools on its way towards the Nordic Seas less atmospheric carbon, compared to pre-industrial times, is absorbed in the water in order to maintain equilibrium with the atmosphere. This is also verified by Anderson and Olsen (2002), who showed, using a simple advective model, that lower latitudes have the largest uptake of anthropogenic  $\text{CO}_2$  from the atmosphere, while higher latitudes have a smaller uptake or even are a source of anthropogenic  $\text{CO}_2$  to the atmosphere. Olsen et al. (2006) used calculated  $\text{pCO}_2$  and measured  $\delta^{13}\text{C}$  values to determine the history of the Atlantic Water; the water masses advected into the Nordic Seas have been exposed to an atmosphere elevated in  $\text{CO}_2$  for a long time and are therefore close to saturated with respect to  $\text{CO}_2$ , hence there will be no further uptake of atmospheric carbon, which is in line with the explanation of Wallace (2001).

The increase in surface carbon over the years at OWSM of about  $1.3 \mu\text{mol kg}^{-1} \text{yr}^{-1}$  (both observed and calculated from salinity normalized carbon concentration in the mixed layer) is also verified by the estimates of anthropogenic carbon increase using the eMLR method. The anthropogenic increase of the mixed layer (excluding the surface water) is estimated to be about  $25 \mu\text{mol kg}^{-1}$  during a period of 24 years (Fig. 8), which equals an annual increase in mixed layer  $C_T$  of about  $1 \mu\text{mol kg}^{-1}$ . From this it seems that the eMLR method, in spite of the large standard deviation, is describing a situation close to the real world for the water in the mixed layer.

For the OWSM deep water, a carbon increase of  $0.57 \pm 0.24 \mu\text{mol kg}^{-1} \text{yr}^{-1}$  is observed based on data from 2001 to 2006. This increase might be due to both natural

and anthropogenic effects. The question might rise if this  $C_T$  increase is a temperature effect. To achieve a temperature induced annual increase in the deep water  $C_T$  of  $0.57 \mu\text{mol kg}^{-1}$ , the deep water temperature must have decreased by about  $0.06^\circ\text{C}$  each year. In contrast to this, Østerhus and Gammelsrød (1999) showed that the temperature of the Norwegian Sea Deep Water increased by about  $0.1^\circ\text{C}$  from 1987 to 1998 and during the period of the present study the temperature has increased by about  $0.004^\circ\text{C}$  per year, which eliminate the deep water  $C_T$  increase as a temperature effect.

So where does the increase in the Norwegian Sea Deep Water  $C_T$  has its origin? The increase must have been brought there by deep or intermediate currents, since there is no deep convection in the Norwegian Sea. The general assumption is that the deep basin of the Norwegian Sea is fed by a mixture of deep water from the Greenland Sea, which traditionally has been colder and fresher than the deep water of the Norwegian Sea, and Arctic Ocean Deep Water, which has been warmer and saltier compared to the Greenland Sea Deep Water (e.g. Swift and Koltermann, 1988). During the 1980s the deep convection in the Greenland Sea slowed down considerably in the sense that the convection was not as deep as previously and only reached intermediate depths (Schlosser et al., 1991). This induced a change in the exchange between the deep basins in the Arctic and Nordic Seas. The older Arctic Ocean Deep Water is lower in dissolved oxygen and higher in carbon and nutrients compared to younger Greenland Sea Deep Water due to more time for remineralisation of organic matter to occur. Blindheim and Rey (2004) compared dissolved oxygen and silicate data from the Greenland Sea Deep Water during the period from 1980s to 2000 and found the oxygen and silicate concentrations to decrease and increase, respectively. This change was attributed to an increased inflow of the older Arctic Ocean Deep Water, which consequently also resulted in a warming of the Greenland Sea Deep Water (Blindheim and Rey, 2004; Blindheim and Østerhus, 2005). Dissolved oxygen and silicate data from the deep water at OWSM is plotted in Fig. 9 and a similar picture with decreasing oxygen and increasing silicate concentrations over the years are also seen

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

here. The change has not been as extensive as in the Greenland Sea, though, with the regression lines showing a decrease in oxygen of about  $0.08 \mu\text{mol kg}^{-1} \text{yr}^{-1}$  and an increase in silicate of about  $0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ . However, the same conclusion can be drawn for the deep Norwegian Sea as for the deep Greenland Sea, that the fraction of the old Arctic Ocean Deep Water has increased compared to previous years. To determine the change in the deep inorganic carbon caused by the changes in water mass composition a Redfield ratio between carbon and oxygen ( $R_{C:O}$ ) of 106:–138 is used (Redfield et al., 1963), and the increase of carbon in the deep water due to decay of organic matter is determined to be  $0.06 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ . This natural process represents about 10% of the observed carbon increase of  $0.57 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ , and consequently, there must be additional explanations for the observed deep water carbon increase at OWSM.

From the eMLR method a deep water anthropogenic  $C_T$  increase of about  $9 \mu\text{mol kg}^{-1}$  over 24 years is estimated. This equals an annual increase of about  $0.4 \mu\text{mol kg}^{-1}$ , which represents the major part of the observed deep water carbon increase at OWSM, and in the following some possible sources for this anthropogenic increase will be discussed. Olsen et al. (2006) estimated an anthropogenic increase in surface water  $C_T$  in the Greenland Sea surface water of between 0.6 and  $0.7 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ . It is reasonable to assume that with an annual deep convection down to about 1500 m in the Greenland Sea (Ronski and Budéus, 2005) the convected water will spread out along isopycnals and enter the deep water circulation, of which a branch is the cyclonic circulation in the Norwegian Sea. It is also reasonable to assume that this transport route might take about 5 years (assuming a deep current speed of  $1 \text{ cm s}^{-1}$ , which is a tenth of the speed in Orvik et al. (2001), who observed an average current speed of the deep water at  $64^\circ \text{N } 1.5^\circ \text{E}$  of about  $10 \text{ cm s}^{-1}$ ). Along the way from the Greenland Sea to OWSM the water is mixed with surrounding waters and the anthropogenic signal might be diluted, but it is difficult to estimate to which extent.

The observed deep water  $C_T$  increase at OWSM might also be explained by turning the view to the Iceland Sea. Blindheim and Rey (2004) suggest that water from the Ice-

**BGD**

4, 2929–2958, 2007

---

## Inorganic carbon time series

I. Skjelvan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

landic Sea is transported further east to join the cyclonic circulation in the deep Norwegian Sea, and this is based on the observed similar characteristics of bottom waters in the Iceland Sea and the deep Norwegian Sea. According to Jónsson (1992) the strong and positive wind-stress curl during winter in the centre of the Icelandic gyre might give reason to deep convection in this area, and hereby bringing an anthropogenic carbon signal down in the water column. A fraction of this newly formed Iceland Sea Deep Water enters the south-western Norwegian Sea, joins the cyclonic gyre there, and finally reaches the OWSM deep water. Another source is found by addressing the recirculated Atlantic Water, which has its origin in the northward flowing Norwegian Atlantic Current where it has got its anthropogenic signal (about  $1 \mu\text{mol kg}^{-1} \text{yr}^{-1}$  to the north of the Boreas Basin surface water according to Olsen et al., 2006). It is sub-ducted in the Fram Strait, and a fraction returns southwards into the Nordic Seas as a component of the East Greenland Current (Rudels et al., 1999). A part of this water continues into the Iceland Sea and enters the East Icelandic Current (e.g. Rudels et al., 2002). On its way the recirculated water is modified due to mixing with surrounding waters and part of this water might finally enter the south-western Norwegian Sea and join the cyclonic circulation of the Norwegian Sea Deep Water. The time from the Atlantic Water leaves the surface to it appears in OWSM deep water is less than 10 years based on an effective current speed of  $1 \text{ cm s}^{-1}$ . In these ways an anthropogenic signal might have been transported towards OWSM via the Iceland Sea and give rise to the observed and estimated annual increase in deep water carbon.

## 6 Summary

Observations of inorganic carbon, nutrients, and hydrography at OWSM in the Norwegian Sea show that over years carbon has increased in the whole water column, and at a higher rate in the surface water compared to the deep water. This increase is verified by an extended multi linear regression method (eMLR). In the surface layer the carbon increase, converted to  $\text{pCO}_2$ , is larger than the observed atmospheric increase, which

**BGD**

4, 2929–2958, 2007

---

### Inorganic carbon time series

I. Skjelvan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

is in contradiction to model results.

The observed deep water carbon increase is of both natural and anthropogenic origin and has several possible explanations; (a) remineralisation due to increased fraction of old Arctic Ocean Deep Water; (b) anthropogenic carbon input via the Greenland Sea surface water; (c) Iceland Sea surface water with a certain anthropogenic carbon signal; and (d) anthropogenic carbon transported with the recirculated Atlantic Water. Remineralisation of organic matter represents about 10% of the deep water carbon increase observed at OWSM, but the pathways of the anthropogenic sources are difficult to quantify.

*Acknowledgements.* Financial support from the Bjerknes Centre for Climate Research (BCCR) and the Geophysical Institute, University of Bergen, is greatly appreciated. The authors are grateful to the captains and crews of M/S Polarfront who kindly did all the water sampling, and to the shipping company Misje Rederi and the Norwegian Meteorological Institute, which gave us permission to use the ship. F. C. Svendsen kindly provided all the bottle salinity data. We also would like to thank our colleagues for fruitful discussions.

## References

- Anderson, L. G. and Olsen, A.: Air-sea flux of anthropogenic carbon dioxide in the North Atlantic, *Geophys. Res. Lett.*, 29, 1835, doi:10.1029/2002GL014820, 2002.
- Blindheim, J. and Rey, F.: Water-mass formation and distribution in the Nordic Seas during the 1990s, *ICES J. Mar. Sci.*, 61, 846–863, 2004.
- Blindheim, J. and Østerhus, S.: The Nordic Seas, Main Oceanographic Features, in: *The Nordic Seas – An integrated perspective*, AGU Geophysical Monograph, 158, edited by: Drange, H., Dokken, T., Furevik, T., Gerdes, R., and Berger, W., 11–37, 2005.
- Dale, T., Rey, F., and Heimdal, B.: Seasonal development of phytoplankton at a high latitude oceanic site, *Sarsia*, 84, 419–435, 1999.
- DOE: Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water, ver. 2, edited by: Dickson, A. G. and Goyet, C., ORNL/CDIAC-74, 1994.

**BGD**

4, 2929–2958, 2007

## Inorganic carbon time series

I. Skjelvan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

- Falck, E. and Anderson, L. G.: The dynamics of the carbon cycle in the surface water of the Norwegian Sea, *Mar. Chem.*, 94, 43–53, 2005.
- Friis, K., Körtzinger, A., Pätsch, J., and Wallace, D. W. R.: On the temporal increase of anthropogenic CO<sub>2</sub> in the subpolar North Atlantic, *Deep-Sea Res. Pt. I*, 52, 681–698, 2005.
- 5 Gislefoss, J. S., Nydal, R., Slagstad, D., Sonninen, E., and Holmén, K.: Carbon time series in the Norwegian Sea, *Deep-Sea Res. Pt. I*, 45, 433–460, 1998.
- Gruber, N., Sarmiento, J. L., and Stocker, T. F.: An improved method for detecting anthropogenic CO<sub>2</sub> in the oceans, *Global Biogeochem. Cy.*, 10, 809–837, 1996.
- IPCC, WP1 AR4 Report: The technical summary, in: The Intergovernmental Panel on Climate Change 4th Assessment Report, available at: <http://www.ipcc.ch/>, 2007.
- 10 Johnson, K. M., Wills, K. D., Butler, D. B., Johnson, W. K., and Wong, C. S.: Coulometric total carbon dioxide analysis for marine studies, *Mar. Chem.*, 44, 167–187, 1993.
- Jónsson, S.: The sources of fresh water in the Iceland Sea and the mechanisms governing its interannual variability, *ICES Marine Science Symposia*, 195, 62–67, 1992.
- 15 Kara, A. B., Rochford, P. A., and Hurlburt, H. E.: An optimal definition for ocean mixed layer depth, *J. Geophys. Res.*, 105, 16 803–16 821, 2000.
- Lewis, E. and Wallace, D. W. R.: Program Developed for CO<sub>2</sub> System Calculations, ORNL/CDIAC-105, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, 1998.
- 20 Mosby, H.: Water, salt and heat balance of the North Polar Sea and of the Norwegian Sea, *Geophysica Norvegica*, 24, 289–313, 1962.
- Nilsen, J. E. Ø. and Falck, E.: Variations of Mixed Layer Properties in the Norwegian Sea for the period 1948-1999, *Prog. Oceanogr.*, 70, 58–90, 2006.
- Olsen, A., Omar, A. M., Bellerby, R. G. J., Johannessen, T., Ninnemann, U., Brown, K. R., Olsson, K. A., Olafsson, J., Nondal, G., Kivimäe, C., Kringstad, S., Neill, C., and Olafsdottir, S.: Magnitude and Origin of the Anthropogenic CO<sub>2</sub> Increase and <sup>13</sup>C Suess Effect in the Nordic Seas Since 1981, *Global Biogeochem. Cy.*, 20, GB3027, doi:10.1029/2005GB002669, 2006.
- 25 Omar, A. and Olsen, A.: Reconstructing the time history of the air-sea CO<sub>2</sub> disequilibrium and its rate of change in eastern subpolar North Atlantic, 1972–1989, *Geophys. Res. Lett.*, 33, L04602, doi:10.1029/2005GL025425, 2006.
- 30 Orvik, K. A., Skagseth, Ø., and Mork, M.: Atlantic Inflow to the Nordic Seas: current structure and volume fluxes from moored current meters, VM-ADCP and SeaSOAR-CTD observa-

**BGD**

4, 2929–2958, 2007

---

**Inorganic carbon  
time series**I. Skjelvan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

- tions, 1995–99, *Deep-Sea Res. Pt. I*, 48, 937–957, 2001.
- Redfield, A. C., Ketchum, B. H., and Richards, F. A.: The influence of organisms on the composition of seawater, in: *The Sea*, edited by: Hill, M. N., John Wiley, New York, 26–77, 1963.
- Rey, F.: Phytoplankton: The grass of the sea, in: *The Norwegian Sea Ecosystem*, edited by: Skjoldal, H. R., Tapir, Trondheim, Norway, 93–132, 2004.
- Ronski, S. and Budéus, G.: Time series of winter convection in the Greenland Sea, *J. Geophys. Res.*, 110, C04015, doi:10.1029/2004JC002318, 2005.
- Rudels, B., Friederich, H. J., and Quadfasel, D.: The Arctic circumpolar boundary current, *Deep-Sea Res. Pt. II*, 46, 1023–1062, 1999.
- Rudels, B., Fahrbach, E., Meincke, J., Budéus, G., and Eriksson, P.: The East Greenland Current and its contribution to the Denmark Strait overflow, *ICES J. Mar. Sci.*, 59, 1133–1154, 2002.
- Sabine, C. L., Key, R. M., Johnson, K. M., Millero, F. J., Poisson, A., Sarmiento, J. L., Wallace, D. W. R., and Winn, C. D.: Anthropogenic CO<sub>2</sub> inventory of the Indian Ocean, *Global Biogeochem. Cy.*, 13, 179–198, 1999.
- Schlosser, P., Bönisch, G., Rhein, M., and Bayer, R.: Reduction of Deepwater Formation in the Greenland Sea During the 1980s: Evidence from Tracer Data, *Science*, 251, 1054–1056, 1991.
- Skjelvan, I., Olsen, A., Anderson, L. G., Bellerby, R. G. J., Falck, E., Kasajima, Y., Kivimäe, C., Omar, A., Rey, F., Olsson, K. A., Johannessen, T., and Heinze, C.: A Review of the Inorganic Carbon Cycle of the Nordic Seas and Barents Sea, in: *The Nordic Seas – An integrated perspective*, AGU Geophysical Monograph, 158, edited by: Drange, H., Dokken, T., Furevik, T., Gerdes, R., and Berger, W., 157–175, 2005.
- Swift, J. H. and Koltermann, K. P.: The origin of Norwegian Sea deep-waters, *J. Geophys. Res.*, 93, 3563–3569, 1988.
- Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metzli, N., Tilbrook, B., Bates, N., Wanninkhof, R., Feely, R. A., Sabine, C., Olafsson, J., and Nojiri, Y.: Global sea-air CO<sub>2</sub> flux based on climatological surface ocean pCO<sub>2</sub>, and seasonal biological and temperature effects, *Deep-Sea Res. Pt. II*, 49, 1601–1622, 2002.
- Tanhua, T. and Wallace, D. W. R.: Consistency of TTO-NAS inorganic carbon data with modern measurements, *Geophys. Res. Lett.*, 32, L14618, doi:10.1029/2005GL023248, 2005.
- Tans, P. P. and Conway, T. J.: Monthly Atmospheric CO<sub>2</sub> Mixing Ratios from the NOAA CMDL Carbon Cycle Cooperative Global Air Sampling Network, 1968-2002, in: *Trends: A Com-*

**BGD**

4, 2929–2958, 2007

---

## Inorganic carbon time series

I. Skjelvan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

pendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A, 2005.

Wallace, D. W. R.: Monitoring global ocean carbon inventories, OOSDP Background Report No. 5, Texas A&M University, College Station, Texas, USA, pp. 54, 1995.

- Wallace, D. W. R.: Storage and transport of excess CO<sub>2</sub> in the oceans: The JGOFS/WOCE global CO<sub>2</sub> Survey, in: Ocean circulation and climate: observing and modelling the global ocean, edited by: Siedler, G., Church, J., and Gould, J., 489–521, 2001.

Østerhus, S. and Gammelsrød, T.: The abyss of the Nordic Seas is warming, J. Climate, 2, 3297–3304, 1999.

**BGD**

4, 2929–2958, 2007

---

**Inorganic carbon  
time series**

I. Skjelvan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

## Inorganic carbon time series

I. Skjelvan et al.

**Table 1.** Typical values of  $C_T$ , nitrate, silicate, temperature, and salinity at OWSM.

	$C_T$ [ $\mu\text{mol kg}^{-1}$ ]	Nitrate [ $\mu\text{mol kg}^{-1}$ ]	Silicate [ $\mu\text{mol kg}^{-1}$ ]	Temperature [ $^{\circ}\text{C}$ ]	Salinity
Surface winter	2140	11.5	5	7	35.2
Surface summer	2040	$\sim 0$	0.5–1	12	34.6–35.1
Deep water	2163	15	12	–0.83	34.91

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Inorganic carbon time series**

I. Skjelvan et al.

**Table 2.** Parameters and coefficients of Eq. (1) for the two different datasets TTO-NAS (1981) and OWSM (2005) determined from the eMLR approach, and statistics connected to the predicted  $C_T$ .

	Salinity		Nitrate	Silicate	$\theta$			
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	$\sigma$	$R^2$	n
TTO-NAS	-1441.67	101.55	3.31	-0.20	-6.65	4.12	0.99	85
OWSM	524.52	45.88	4.66	-2.88	-5.41	5.63	0.95	162

$\theta$  is the potential temperature.

*a*, *b*, *c*, *d*, and *e* are regression coefficients specific for the particular dataset.

$\sigma$ ,  $R^2$ , and n are the standard deviation, relative predictive power of the model, and number of data points used, respectively.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

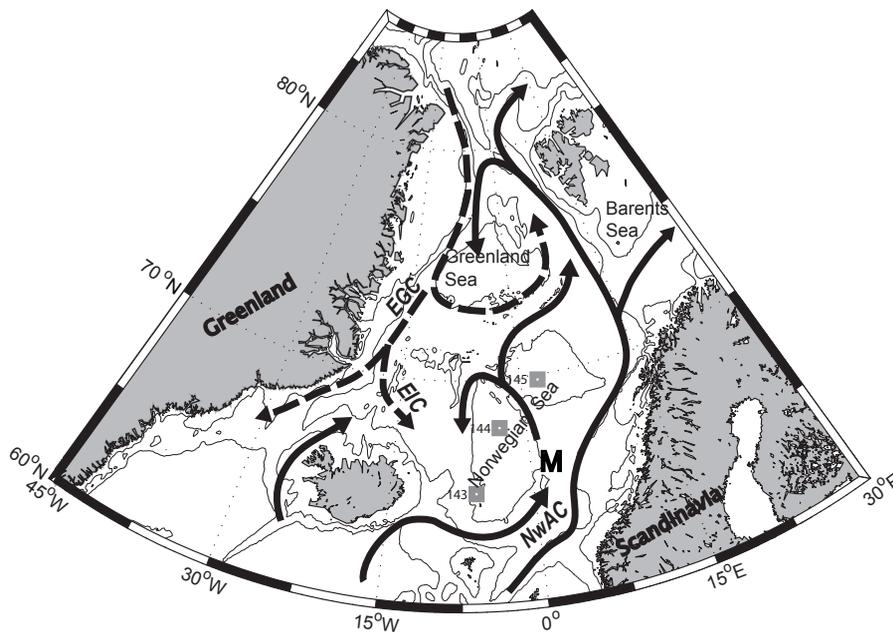
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Inorganic carbon  
time series

I. Skjelvan et al.



**Fig. 1.** Schematic of the northern North Atlantic Ocean. The solid lines indicate the flow of warm Atlantic Water and the dashed lines show the flow of cold Polar and Arctic Water. NwAC is the Norwegian Atlantic Current, EGC is the East Greenland Current, and EIC is the East Icelandic Current. M denotes Ocean Weather Station M (OWSM) and the grey squares indicate TTO stations used for estimating anthropogenic carbon increase at OWSM.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

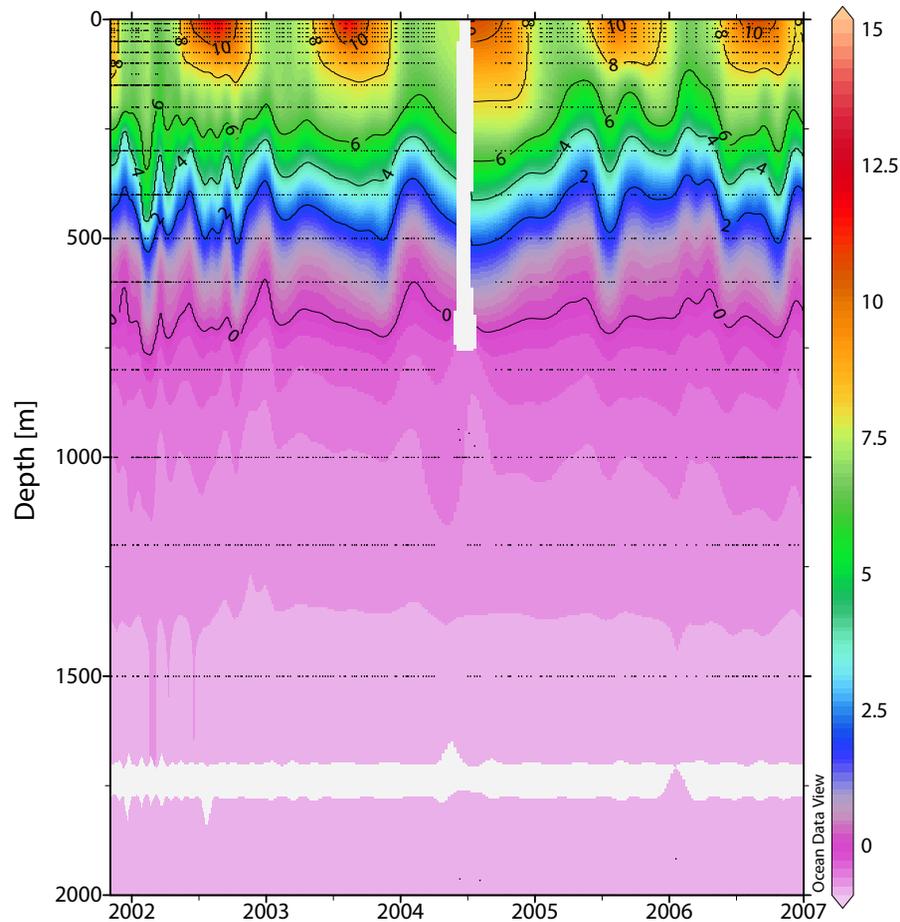
Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 2.** Hovmöller diagram of water column temperature during the period 2001 through 2007.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Inorganic carbon  
time series

I. Skjelvan et al.

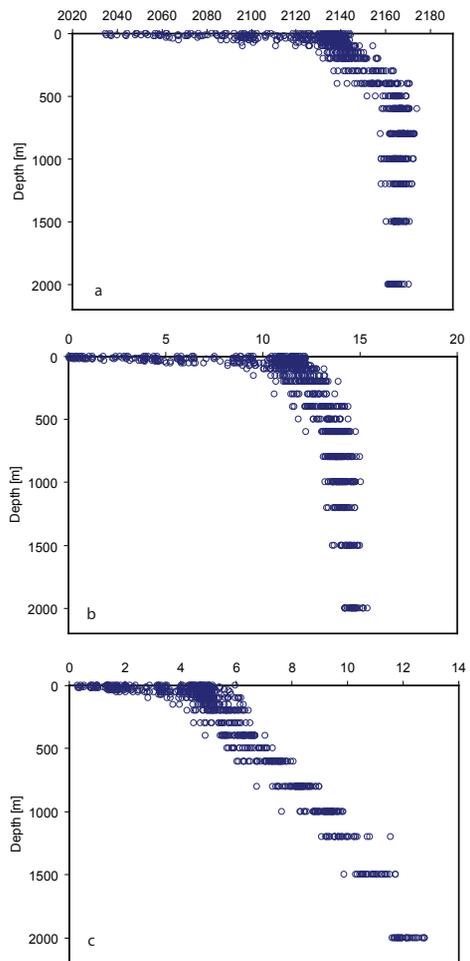


Fig. 3. (a)  $C_7$ , (b) nitrate, and (c) silicate data from 2001 to 2006.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

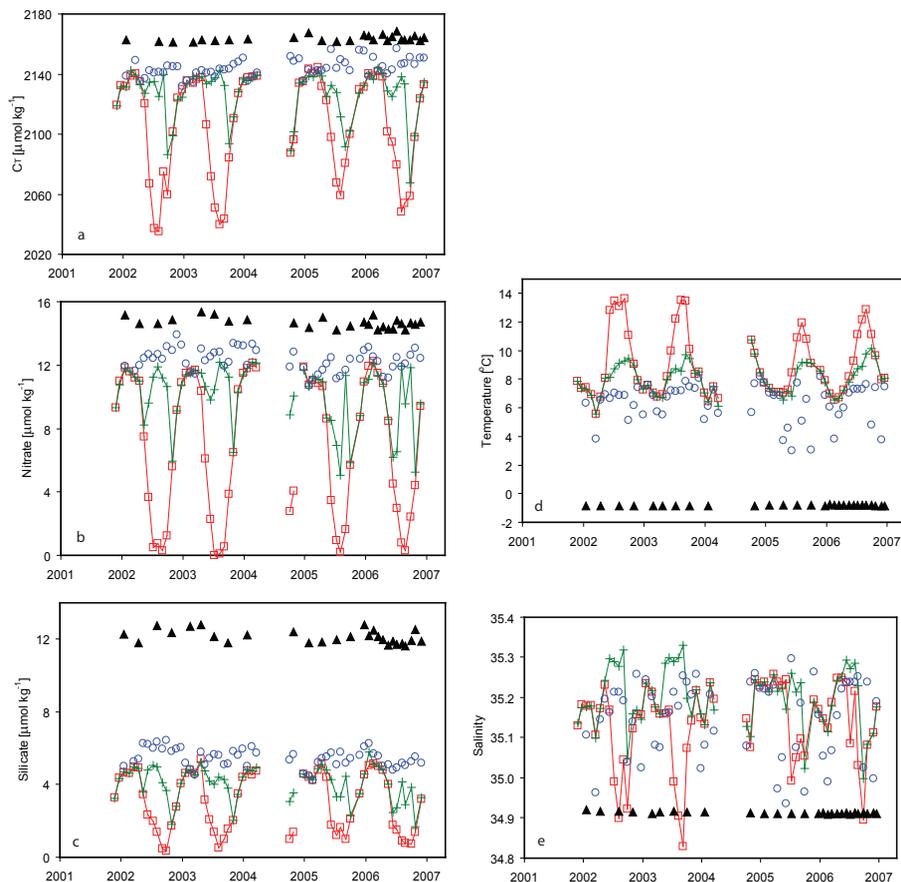
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Inorganic carbon  
time series

I. Skjelvan et al.

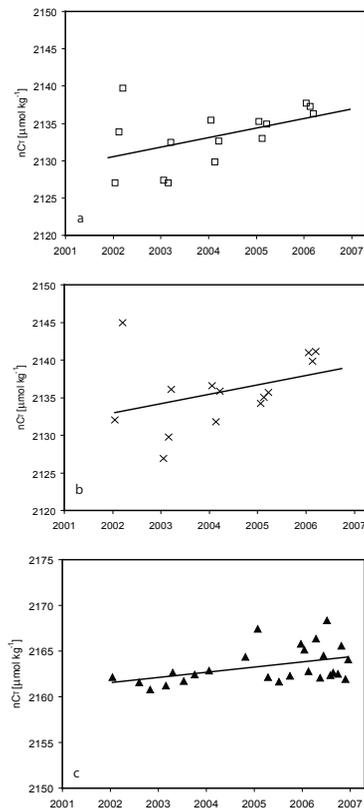


**Fig. 4.** Seasonal variations in **(a)**  $C_T$ , **(b)** nitrate, **(c)** silicate, **(d)** temperature, and **(e)** salinity at different depths as a function of time. Red squares are at 10 m, green crosses are at 50 m, blue circles are at 200 m, and black filled triangles are at 2000 m depth.

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

Inorganic carbon  
time series

I. Skjelvan et al.



**Fig. 5.** Salinity normalized carbon concentration over the period 2002–2006 in **(a)** the surface water during the winter months January to March, **(b)** the mixed layer during the winter months January to March, and **(c)** the deep water (four times a year in 2002–2004, and once a month from 2005 and onwards). The surface  $C_7$  samples are normalized to a salinity of 35.1, while the deep water samples are normalized to a salinity of 34.91.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

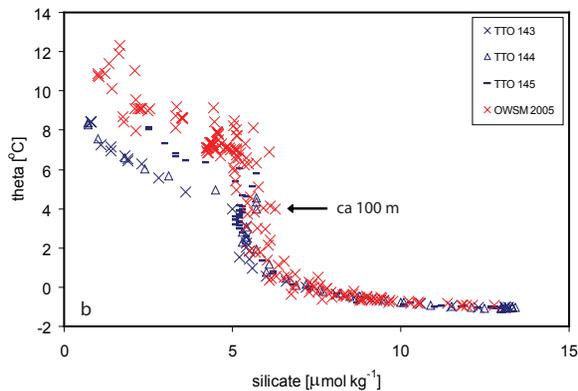
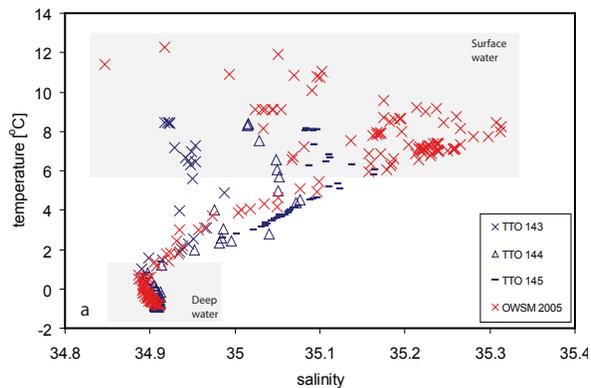
Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 6.** (a) Temperature vs. salinity and (b) theta (potential temperature) vs. silicate, based on data from TTO-NAS stations 1981 (different blue symbols, see Fig. 1) and OWSM 2005 (red crosses).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

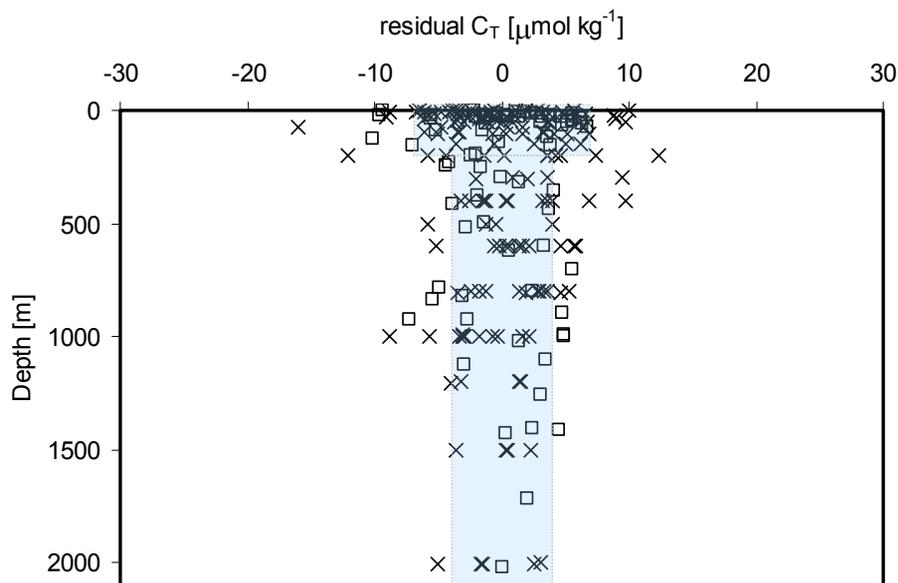
Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

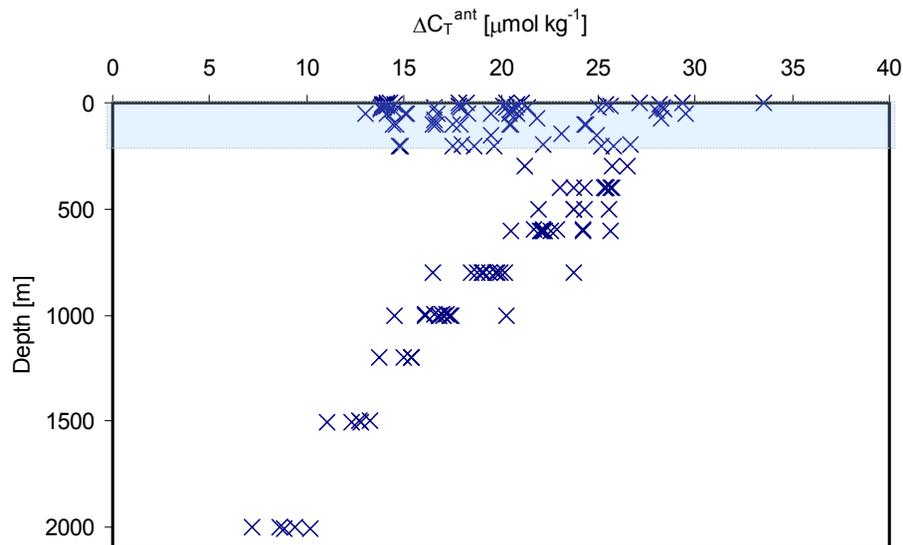


**Fig. 7.** Residuals of  $C_T$  (measured minus predicted value) as a function of depth; TTO-NAS 1981 (squares) and at OWSM 2005 (crosses). The shaded area indicates the accuracy of the eMLR method of  $\pm 7 \mu\text{mol kg}^{-1}$  in the upper 200 m and  $\pm 4 \mu\text{mol kg}^{-1}$  in the deeper layers.

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

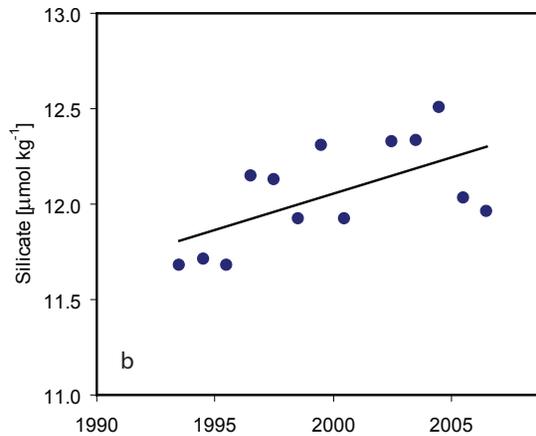
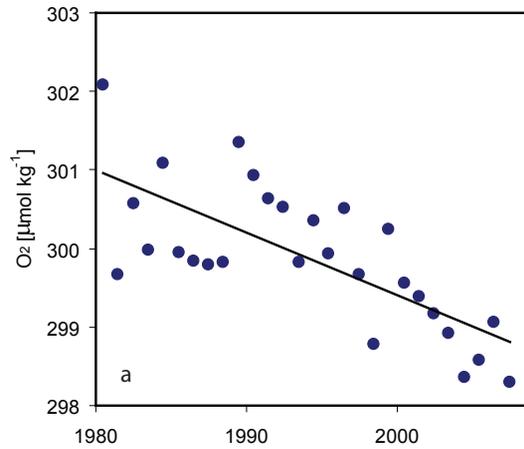
Inorganic carbon  
time series

I. Skjelvan et al.



**Fig. 8.** Amount of anthropogenic carbon entered into the water column at OWSM from 1981 to 2005. The shaded area indicates that in the upper waters the method is less accurate than deeper in the water column.

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



**Fig. 9.** Annual means of **(a)** dissolved oxygen and **(b)** silicate over the years at 2000 m depth at OWSM, with regression lines.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion