

This discussion paper is/has been under review for the journal Biogeosciences (BG).
 Please refer to the corresponding final paper in BG if available.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé¹, N. Metzl¹, C. Pierre¹, G. Reverdin¹, P. D. Quay², and S. R. Olafsdottir³

¹CNRS/INSU/IRD/ Université Pierre et Marie Curie, UMR7159, LOCEAN: Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques, boîte 100, 4 Place Jussieu – 75252 Paris Cedex 05, France

²School of Oceanography, University of Washington, Seattle, Washington, USA

³Marine Research Institute, Skulagata 4, IS 121 Reykjavik, Iceland

Received: 12 August 2013 – Accepted: 19 August 2013 – Published: 29 August 2013

Correspondence to: V. Racapé (vrlod@locean-ipsl.upmc.fr)

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

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

This study introduces for the first time the $\delta^{13}\text{C}_{\text{DIC}}$ seasonality in the North Atlantic Subpolar Gyre (NASPG) using $\delta^{13}\text{C}_{\text{DIC}}$ data obtained between 2005 and 2012 with Dissolved Inorganic Carbon (DIC) and nutrient observations. On the seasonal scale, the NASPG is characterized by higher $\delta^{13}\text{C}_{\text{DIC}}$ values during summer than during winter with seasonal amplitude of 0.77 ‰. This is attributed to biological activity in summer and to deep remineralization process during winter convection. During all seasons, we observed a strong linear relationship between $\delta^{13}\text{C}_{\text{DIC}}$ and DIC. Results also revealed a negative anomaly for DIC and nutrients in August 2010 that could be explained by a coccolithophore bloom associated to a warming up to +2 °C. Winter data also showed a large decrease in $\delta^{13}\text{C}_{\text{DIC}}$ associated with an increase in DIC between 2006 and 2011–2012 but with observed time rates (-0.04‰yr^{-1} and $+1.7\text{ }\mu\text{mol kg}^{-1}\text{ yr}^{-1}$) much larger than the expected anthropogenic signal.

1 Introduction

The stable isotopic composition of dissolved inorganic carbon (DIC) in the ocean is a useful semi-conservative tracer for various oceanic analysis (e.g. water masses, paleo-circulation) and global carbon studies (constraint for global carbon budget, interpreting anthropogenic carbon). This is reported relative to the reference V-PDB (Vienna – Pee Dee Belemnite) in terms of $\delta^{13}\text{C}$ in ‰ (Craig, 1957):

$$\delta^{13}\text{C} = \left[\frac{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{sample}}}{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{reference}}} - 1 \right] \times 1000 \quad (1)$$

The mean annual large scale distribution of this tracer is now relatively well documented at surface and at depth. Values range typically between 0.5 and 2.5 ‰ in the

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



modern surface ocean (Gruber et al., 1999). Regular observations conducted since the 1970–80s at a few time series stations or repetitive tracks were used to describe and interpret its temporal variability. In subtropical oceanic regions, the seasonal amplitude of 0.2–0.3‰ at the BATS station (Bermuda Atlantic Time series) and of 0.1‰ at the ALOHA station (Pacific time series north of Hawaii) reflect the local balance between air-sea CO_2 exchange, biological activity and vertical mixing (Gruber et al., 1998, 1999; Gruber and Keeling, 1999; Quay and Stutsman, 2003). This is also observed in the Southern Indian Ocean with seasonal amplitude of 0.3‰ in the western part of the basin (Racapé et al., 2010), whereas it reaches 0.45‰ south of Tasmania (McNeil and Tilbrook, 2009). Studies have also highlighted a significant decrease in $\delta^{13}\text{C}_{\text{DIC}}$ attributed to the anthropogenic CO_2 uptake in the ocean. This results from human-induced perturbations which reduce the $\delta^{13}\text{C}_{\text{CO}_2}$ in the atmosphere with a time rate of change of -0.24‰d^{-1} (estimate for the period 1985–2008 with Alert station data set, Keeling et al., 2010), as the combustion of the organic carbon pool produces CO_2 gas is strongly depleted in heavy carbon isotope (^{13}C). This signal, known as the oceanic ^{13}C Suess effect, provides an additional constraint to estimate the anthropogenic carbon uptake in the ocean. This has been estimated to be less than -0.07‰d^{-1} in polar regions (McNeil et al., 2001; Olsen et al., 2006; Sonnerup and Quay, 2012) and as large as -0.25‰d^{-1} in subtropical regions (Bacastow et al., 1996; Gruber et al., 1999; Sonnerup and Quay, 2012). The high latitudes of the North Atlantic Ocean are considered as one of the strongest anthropogenic CO_2 sink, a consequence of the large heat loss and deep convection during winter as well as a strong biological activity during spring and summer. In this region, the temporal variability (seasonal to decadal) of the $\delta^{13}\text{C}_{\text{DIC}}$ still needs to be investigated. The winter-summer difference is expected to be as large as 1‰ (Gruber et al., 1999) that could potentially mask the oceanic ^{13}C Suess effect in surface water (McNeil et al., 2001). In this context, this study introduces for the first time the $\delta^{13}\text{C}_{\text{DIC}}$ seasonality in the North Atlantic subpolar gyre using $\delta^{13}\text{C}_{\text{DIC}}$ surface data obtained between 2005 and 2012 from merchant vessels Skogafoss and Reykjafoss (14 cruises) along with DIC and nutrient measurements.

Driving processes will be identified from isotopic data and from the semi-quantitative tracer ($\Delta\delta^{13}\text{C}_{\text{bio}}$) of Gruber et al. (1999) which enables to isolate the biological contribution to the seasonal amplitude from the physical contributions (e.g. air-sea gas exchange fractionation, ocean dynamics). The time rate of change in $\delta^{13}\text{C}_{\text{DIC}}$ will be investigated over the short period of 7 yr and compared to other regions.

2 Materials and methods

2.1 Data collection

Data used in this study were collected in the North Atlantic subpolar gyre mostly from merchant vessels Skogafoss and Reykjafoss between Reykjavik (64.15° N to 21.85° W, Iceland) and Newfoundland (47.30° N to 53.98° W, Canada; Fig. 1) over two periods in 2005–2006 and 2010–2012. This is part of sampling efforts carried from vessels of opportunity within the SURATLANT project initiated in 1993. The sampling periods for each cruise and vessel were summarized in Table 1.

During all cruises, sea-water was pumped from a depth of $\sim 3\text{--}5$ m depending on the ship. Sea Surface Salinity (SSS) was from discrete salinity samples. Sea Surface Temperature (SST) is either from continuously recording ThermoSalinoGraph (TSG seabird Electronics, Inc. USA, model 21) corrected for an average bias to sea surface temperature, or from nearly simultaneous XBT temperature profiles (at 3 m). SST and SSS accuracies were estimated to be 0.2 °C and 0.01, respectively. $\delta^{13}\text{C}_{\text{DIC}}$, DIC and nitrate concentrations (NO_3^-) were also obtained from discrete samples collected every 4 h and analysed later in land laboratories. Over the period 2005–depending on season and with higher 2006, DIC samples were estimated manometrically during acid CO_2 extraction procedure for $\delta^{13}\text{C}_{\text{DIC}}$ measurements from helium stripping technique. This analytical method has been described previously by Quay et al. (1992, 2003). These measurements have an accuracy about $\pm 0.02\text{‰}$ for $\delta^{13}\text{C}_{\text{DIC}}$ based on a helium stripping technique adapted from the one used by Kroopnick (1974) and $\pm 5\ \mu\text{mol kg}^{-1}$ for

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

DIC based on a comparison to coulometric DIC values and to Certified Reference Material (CRM) provided by A. Dickson (Scripps Institution of Oceanography, San Diego, USA). Over the period 2010–2012 during the SURATLANT cruises, $\delta^{13}\text{C}_{\text{DIC}}$ were measured via an acid CO_2 extraction method in a vacuum system developed by Kroopnick (1974) whereas DIC were determined at the same time as total alkalinity (Alk) by a potentiometric titration using CRM calibration (Edmond, 1970). Further details on the sampling methods and analytical techniques are provided in Racapé et al. (2010, 2013) for $\delta^{13}\text{C}_{\text{DIC}}$ and in Corbière et al. (2007) and Metzl et al. (2010) for DIC. Both parameters were analyzed at the LOCEAN-IPSL Laboratory (Paris, France) and have an accuracy close to $\pm 0.02\text{‰}$ (Vangriesheim et al., 2009; Racapé et al., 2010) and $\pm 3\text{ }\mu\text{mol kg}^{-1}$. Finally, nutrient concentrations were measured for all cruises with standard colorimetric methods at the Marine Research Institute (Reykjavik, Iceland). The analytical procedure and the quality control for the nutrient analysis has been described in detail in Olafsson et al. (2009) where the long term accuracy has been estimated of $\pm 0.2\text{ }\mu\text{mol L}^{-1}$ for nitrate and silicate, and $0.03\text{ }\mu\text{mol L}^{-1}$ for phosphate.

2.2 $\Delta\delta^{13}\text{C}_{\text{bio}}$ and $\delta^{13}\text{C}_{\text{phy}}$ estimation

To determine the major process driving the seasonal $\delta^{13}\text{C}_{\text{DIC}}$ distribution, we used an isotopic and semi-quantitative tracer of Gruber et al. (1999), noted $\Delta\delta^{13}\text{C}_{\text{bio}}$. Described as the biological signature, this results from the combined photosynthesis, respiration and remineralization processes (the soft-tissue pump) as well as the formation-dissolution of the calcium carbonate shells (the carbonate pump). The $\Delta\delta^{13}\text{C}_{\text{bio}}$ will be expressed from winter (W) to summer (S) conditions according to Eq. (2), with the stoichiometric carbon-nitrate ratio ($r_{c:n}$) of 117 : 16 from Anderson and Sarmiento (1994), the $\delta^{13}\text{C}$ value of the carbonate pump ($\delta^{13}\text{C}_{\text{carb}}$) of 2‰ like Gruber et al. (1999) and the $\delta^{13}\text{C}$ value of organic matter ($\delta^{13}\text{C}_{\text{org}}$) of around -24‰ from Goericke and Fry (1994). This last value depicts the average for the northern North Atlantic where sea surface

temperature is around 10°C in summer:

$$\Delta\delta^{13}\text{C}_{\text{bio}}^{\text{W}\rightarrow\text{S}} = r_{\text{C:n}} \times \delta^{13}\text{C}_{\text{org}} \times \frac{(\text{NO}_3^{\text{S}} - \text{NO}_3^{\text{W}})}{\text{DIC}^{\text{S}} + \delta^{13}\text{C}_{\text{carb}}} \times \frac{(\text{Alk}^{\text{S}} - \text{Alk}^{\text{W}} + \text{NO}_3^{\text{S}} - \text{NO}_3^{\text{W}})}{2\text{DIC}^{\text{S}}} \quad (2)$$

As biological fractionation associated to the carbonate pump does not contribute much to the biological signature (< 0.02‰ the measurement error), this mechanism will be afterwards neglected. The difference between the summer $\delta^{13}\text{C}_{\text{DIC}}$ and the expected $\delta^{13}\text{C}_{\text{DIC}}$ if biological activity was the only process controlling the seasonal distribution, corresponds to physical processes ($\delta^{13}\text{C}_{\text{phy}}$, air-sea CO_2 exchange and ocean dynamics; Eq. (3) which also contribute to the seasonal variation:

$$\delta^{13}\text{C}_{\text{phy}}^{\text{W}\rightarrow\text{S}} = \delta^{13}\text{C}_{\text{DIC}}^{\text{S}} - (\delta^{13}\text{C}_{\text{DIC}}^{\text{W}} + \Delta\delta^{13}\text{C}_{\text{bio}}^{\text{W}\rightarrow\text{S}}) \quad (3)$$

3 Results and discussion

3.1 Surface $\delta^{13}\text{C}_{\text{DIC}}$ distribution

During each transect, surface $\delta^{13}\text{C}_{\text{DIC}}$ is distributed according to a north-south gradient with an amplitude between 0.2‰ and 0.4‰ depending on season and with higher values close to Newfoundland coast (up to 1.8‰; Fig. 2a and c). This is opposite to the DIC gradient (up to 100 $\mu\text{mol kg}^{-1}$; Fig. 2b and d) which increases northward as observed previously by Corbière et al. (2007). The authors have also shown that the area south of 53° N was characterized by a large spatial variability in SST, SSS as well as carbon and nutrients properties when crossing the Labrador Current and approaching the Newfoundland coast (Fig. 1). This variability is also found in $\delta^{13}\text{C}_{\text{DIC}}$ distribution (Fig. 2). Influence of coastal waters was also identified north of 62° N near Iceland. Thus, we selected a region where both hydrological and carbon properties including $\delta^{13}\text{C}_{\text{DIC}}$ are much more homogeneous between 53 and 62° N which corresponds to

the interior of the North Atlantic SubPolar Gyre, denoted NASPG, west of the Reykjanes Ridge.

In the NASPG, the $\delta^{13}\text{C}_{\text{DIC}}$ meridional gradient is weaker (close to 0.1‰). Largest values were observed during summer (up to $1.65 \pm 0.10\text{‰}$ in 2005–2006 and $1.36 \pm 0.11\text{‰}$ in 2010–2012) while minima were measured during winter (down to $0.87 \pm 0.05\text{‰}$ in 2005–2006 and $0.61 \pm 0.04\text{‰}$ in 2010–2012), conversely for DIC (Fig. 2 and Table 1). Compared to 2005–2006, $\delta^{13}\text{C}_{\text{DIC}}$ values collected in 2010–2012 seems to be lower (and DIC higher), suggesting a potential impact of anthropogenic carbon uptake. This would then require the correction of $\delta^{13}\text{C}_{\text{DIC}}$ observations by this anthropogenic signal to compose the ‘climatological’ seasonal cycle. If this change in $\delta^{13}\text{C}_{\text{DIC}}$ (decrease) was only attributed to the oceanic ^{13}C Suess effect, this should be also observed on DIC with an expected theoretical DIC increase of 5–7 $\mu\text{mol kg}^{-1}$ (Corbière et al., 2007; Metzl et al., 2010). We now investigate the relation between DIC and $\delta^{13}\text{C}_{\text{DIC}}$.

3.2 $\delta^{13}\text{C}_{\text{DIC}}$ vs. DIC in NASPG

Figure 3a reveals a strong link between $\delta^{13}\text{C}_{\text{DIC}}$ and DIC concentration in the NASPG with a large anomaly in August 2010, clearly outside the general trend. High productivity recorded in the whole region during the summer 2010 (Fig. 4a) would explain the low DIC concentration measured in the basin ($2054.40 \pm 9.92 \mu\text{mol kg}^{-1}$, Table 1). This should be associated with a positive anomaly in $\delta^{13}\text{C}_{\text{DIC}}$ but observed values are not as large as expected. An additional driving process reducing $\delta^{13}\text{C}_{\text{DIC}}$ could mask the biological signal. Data collected in December 2010 are relatively higher in $\delta^{13}\text{C}_{\text{DIC}}$ and lower in DIC than those sampled in December 2011, may be a consequence of the anomaly observed in August 2010. August and December 2010 will not be included to evaluate the relationship between DIC and $\delta^{13}\text{C}_{\text{DIC}}$. Because only 4 data were sampled in the south of the transect, June 2006 will also not be used to estimate this relation.

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Except for November 2006, all data collected in 2005–2006 seem to be organized linearly above those sampled between 2010 and 2012. Mean values estimated for both parameters (Fig. 3b and Table 1) corroborate this result.

Thus, two linear regressions are deduced from the two data sets: July 2005 to April 2006 and March 2011–September 2012 (Eqs. 4 and 5):

$$\delta^{13}\text{C}_{\text{DIC}}^{2005-2006} = -0.0112 \times [\text{DIC}] + 24.869 \quad r^2 = 0.95 \quad (4)$$

$$\delta^{13}\text{C}_{\text{DIC}}^{2011-2012} = -0.0108 \times [\text{DIC}] + 23.810 \quad r^2 = 0.95 \quad (5)$$

Based on a Student's *t* test, there is no significant difference between the slopes of these two regressions. In addition, these two slopes are equivalent to those expected if the organic carbon production and respiration were the only processes affecting DIC and $\delta^{13}\text{C}_{\text{DIC}}$ distributions (-0.011‰ ($\mu\text{mol kg}^{-1}$) with $\delta^{13}\text{C}_{\text{org}}$ of -24‰ and $r_{c:n}$ of 117:16).

Figure 3 also enables to highlight an important signal to interpret the seasonality. If we focus on the winter data set (February–March), we notice an increase in DIC by $10\mu\text{mol kg}^{-1}$ and a decrease in $\delta^{13}\text{C}_{\text{DIC}}$ by -0.26‰ from 2006 to 2012 (Table 1). These observed time rates of change ($+1.7(\mu\text{mol kg}^{-1})\text{yr}^{-1}$ and -0.04‰yr^{-1}) are much larger than those expected from the anthropogenic effect (respectively, $\sim 1(\mu\text{mol kg}^{-1})\text{yr}^{-1}$ from Corbière et al. (2007) and Metzl et al. (2010) and between -0.014‰yr^{-1} following Sonnerup and Quay, 2012 and -0.024‰yr^{-1} according to Olsen et al., 2006) suggesting a significant additional contribution of natural variability in the NASPG region. The mixed layer depth time series depicted on Fig. 4b reveals two deep winter episodes which should be associated to a higher DI^{13}C input of subsurface water, reducing thus $\delta^{13}\text{C}_{\text{DIC}}$ (and increasing DIC). Because of this large natural variability, observations are not corrected of an anthropogenic signal and the mean $\delta^{13}\text{C}_{\text{DIC}}$ seasonal cycle will be composed for the 2005–2006 yr period.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3 $\delta^{13}\text{C}_{\text{DIC}}$ seasonal cycle and driving processes in NASPG

Based on satellite information (monthly SST composite of MODIS Aqua 9 km, disc.sci.gsfc.nasa.gov/giovanni) SURATLANT data set (NO_3^- and DIC) and Eq. (4), we built the climatological seasonal cycle of SST, NO_3^- , DIC and $\delta^{13}\text{C}_{\text{DIC}}$ for 2005–2006 (Fig. 5). Because DIC concentration has slightly changed during this period (by less than the climatological cycle standard deviation; Corbière et al., 2007; Ullman et al., 2009), we chose to consider the available DIC (and NO_3^-) data set sampled between 2001 and 2006, which are much more complete to compose the seasonality. The observations collected on board the M/V Skogafoss in 2005–2006 fit well within this climatology (Fig. 5b and c).

Figure 5 reveals thus the mean seasonal cycle for $\delta^{13}\text{C}_{\text{DIC}}$ with an amplitude of 0.77‰, in phase with SST (6°C) and in opposite phase with NO_3^- (9 $\mu\text{mol kg}^{-1}$) and DIC (70 $\mu\text{mol kg}^{-1}$). Minima are observed in February–March whereas maxima are estimated in August during the summer bloom (Antoine et al., 2005; Corbière et al., 2007). Based on the Eqs. (2) and (3), processes controlling this seasonality could be identified. Table 2 summarizes the results. The standard deviation estimated here displays the meridional gradient reported previously. Positive $\Delta\delta^{13}\text{C}_{\text{bio}}$ is associated with phytoplankton activity, which uses preferentially the light carbon isotope during the photosynthetic mechanism ($\Delta\text{NO}_3^{\text{W}\rightarrow\text{S}} < 0 \mu\text{mol kg}^{-1}$, nutrient consumption), whereas negative $\Delta\delta^{13}\text{C}_{\text{bio}}$ highlights a remineralization process, which releases much more DI^{12}C ($\Delta\text{NO}_3^{\text{W}\rightarrow\text{S}} > 0$, Nutrient input). Based on climatological values (Fig. 4), we estimate a $\Delta\delta^{13}\text{C}_{\text{bio}}$ of 0.74 ± 0.12 ‰ for the winter to summer amplitude of 0.77 ± 0.07 ‰. In the NASPG surface water, the $\delta^{13}\text{C}_{\text{DIC}}$ seasonality is largely controlled by biological activity, which enhanced $\delta^{13}\text{C}_{\text{DIC}}$ values during summer (photosynthesis) and decreased them during winter (remineralization). This high remineralized concentration of NO_3^- and DIC concentrations are attributed to the winter entrainment of subsurface water (Takahashi et al., 1993). The biological $\delta^{13}\text{C}_{\text{DIC}}$ signature estimated from winter

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

to summer 2010 (August 2010) is much higher ($1.00 \pm 0.10\%$) than those obtained from the climatological data set. This is in agreement with the first hypothesis of the high productivity. The lack of $\delta^{13}\text{C}_{\text{DIC}}$ measurement in winter 2010 precludes estimating directly $\delta^{13}\text{C}_{\text{phy}}$. If photosynthesis was the only process controlling the winter to summer amplitude as we have observed with the climatological cycle, $\delta^{13}\text{C}_{\text{DIC}}$ values of winter 2010 would be around 0.37% ($\delta^{13}\text{C}_{\text{DIC}}^{\text{August 2010}} + \Delta\delta^{13}\text{C}_{\text{bio}}^{\text{W} \rightarrow \text{August 2010}} = 1.3 - 0.99$). Such low values have not yet been observed in the NASPG (Quay et al., 2007; Racapé et al., 2013) and are unlikely. This suggests either the contribution of physical mechanisms partially canceling the biological effect or the overestimate of the $\Delta\delta^{13}\text{C}_{\text{bio}}$ largely dependent on the winter to summer NO_3^- gradient. In addition, the NASPG experienced a significant warming ($+2^\circ\text{C}$) during 2010. Associated to a shallow mixed layer depth (15 m; Fig. 4b) and an unusually low concentration in nitrate (Fig. 5b), such environmental conditions would promote coccolithophore bloom in this subpolar region (Raitsos et al., 2006). As a small ^{13}C fractionation occurs during formation of calcium carbonate shells, a coccolithophore bloom reduces DIC by their carbonate pump but without significant change in $\delta^{13}\text{C}_{\text{DIC}}$. This could explain the large decrease only observed in DIC concentrations in August 2010. This DIC concentration is indeed lower than September 2012 whereas $\delta^{13}\text{C}_{\text{DIC}}$ values are comparable. The cloudy conditions during summer 2010 precluded observations with satellite imagery, so that it is difficult to confirm this hypothesis. Coccolithophore blooms been not expected at the end of summer and later on, we expected a seasonal change in $\delta^{13}\text{C}_{\text{DIC}}$ and DIC according to a slope of -0.011% ($\mu\text{mol kg}^{-1}$) as for the climatology. Based on Fig. 3, these two parameters change nevertheless with a rate of -0.007% ($\mu\text{mol kg}^{-1}$) between August 2010 and March 2011, suggesting a more important impact of physical processes masking thus the biological effect. Estimation of the biological and physical contribution from August to December 2010 emphasizes this hypothesis ($\delta^{13}\text{C}_{\text{phy}} >$ climatological $\delta^{13}\text{C}_{\text{phy}}$). Finally, results for November 2006 indicate that physical processes such as horizontal or vertical transport can contribute to controlling the $\delta^{13}\text{C}_{\text{DIC}}$

decrease $\delta^{13}\text{C}_{\text{phy}} < \text{climatological } \delta^{13}\text{C}_{\text{phy}}$). However, as no anomaly is detected in November 2006 in DIC concentration (Fig. 5c) and in mixed layer depth (Fig. 4b), this is difficult to assess further.

4 Conclusions

5 In this study, we presented new sea surface observations of $\delta^{13}\text{C}_{\text{DIC}}$ and associated hydrological and biogeochemical properties (DIC, NO_3^-) in the NASPG (53–62° N) based on 14 transects conducted between 2005 and 2012. During all transects, we observed a positive north-south gradient coherent with model-studies of Gruber et al. (1999) and Tagliabue and Bopp (2008) and opposite to DIC gradients (high DIC
10 in the north, low in the south). We have also detected a very large range of $\delta^{13}\text{C}_{\text{DIC}}$ depending on the periods. Coupling $\delta^{13}\text{C}_{\text{DIC}}$ -DIC observations enabled to reveal strong parallel relationships for each period (2005–2006, 2010–2012). For both tracers and for winter (February–March) the change from 2005–2006 to 2010–2012 is coherent with anthropogenic carbon uptake (increase in DIC, decrease in $\delta^{13}\text{C}_{\text{DIC}}$) but with a
15 time rate change much larger than the theoretical change due to anthropogenic effect. Deeper winter mixing recorded in winter 2008–2009 and in winter 2011–2012 contribute most likely to reduce $\delta^{13}\text{C}_{\text{DIC}}$ and increase DIC masking thus the anthropogenic signal. The $\delta^{13}\text{C}_{\text{DIC}}$ -DIC relationships has also helped to identify large anomalies occurring in November 2006 (low $\delta^{13}\text{C}_{\text{DIC}}$), December 2010 (low DIC, high $\delta^{13}\text{C}_{\text{DIC}}$) and
20 August 2010 (low DIC related to an enhanced coccolithophore bloom).

The seasonality of $\delta^{13}\text{C}_{\text{DIC}}$ in this region was investigated taking into account the observed changes (over 7 yr and not accounting for large anomalies) and was computed for years 2005–2006. Our “climatological” seasonal cycle shows a large variation of 0.77‰ (larger in summer, lower in winter) which represents the largest seasonal amplitude recorded at the sea surface. This is coherent with large DIC ($70 \mu\text{mol kg}^{-1}$),
25 nutrients and $p\text{CO}_2$ seasonal signals previously observed in the region (Corbière et

BGD

10, 14515–14537, 2013

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



al., 2007). A diagnostic process model suggests that the biological processes control the $\delta^{13}\text{C}_{\text{DIC}}$ seasonality, masking thus air-sea gas exchange and ocean dynamic effect. The comparison between the slope obtained from $\delta^{13}\text{C}_{\text{DIC}}$ -DIC relationship and those expected if the soft-tissue pump is the only driving process, emphasized the importance of the biological pump on DIC seasonality in the Subpolar North Atlantic region. The observed $\delta^{13}\text{C}_{\text{DIC}}$ seasonal cycle being now well established, a challenge for future analysis will be to investigate this seasonality in ocean models. For investigating the anthropogenic signals, we strongly recommend to maintain such observations in the future. This highlights the need to continue observing both parameters to separate natural and anthropogenic signals, as well as to better constrain atmospheric inversions and validate ocean carbon models.

Acknowledgements. This study has been supported EU FP7 project CARBOCHANGE (264879), by CNRS/INSU in France (O. R. E. SSS and OCEANS-C13 projects). We thank the EIMSKIP Company, the captains and crews of the MV *Skogafoss* and the MV *Reykjafoss*, all the very helpful embarked observers for the ^{13}C and DIC sampling, A.Naamar and the SNAPO-CO₂ for their help in laboratory analysis, Cesar Deschamps-Berger for the MLD time series. We thank also L. Bopp for fruitful discussions.



The publication of this article is financed by CNRS-INSU.

References

Anderson, L. A. and Sarmiento, J. L.: Redfield ratios of remineralization determined by nutrient data analysis, *Global Biogeochem. Cy.*, 8, 65–80, 1994.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Antoine, D., Morel, A., Gordon, H. R., Banzon, V. F., and Evans, R. H.: Bridging ocean color observations of the 1980s and 2000s in search of long term trends, *J. Geophys. Res.*, 110, C06009, doi:10.1029/2004JC002620, 2005.

Bacastow, R. B., Keeling, C. D., Lueken, T. J., Wahlen, M., and Mook, W. G.: The ^{13}C Suess effect in the world surface oceans and its implications for oceanic uptake of CO_2 : analysis of observations at Bermuda, *Global Biogeochem. Cy.*, 10, 335–346, 1996.

Corbière, A., Metz, N., Reverdin, G., Brunet, C., and Takahashi, T.: Interannual and decadal variability of the oceanic carbon sink in the North Atlantic Subpolar Gyre, *Tellus B*, 59, 168–178, doi:10.1111/j.1600-0889.2006.00232.x, 2007.

Craig, H.: Isotopic standards for carbon and oxygen and correction factor for mass-spectrometric analysis of carbon dioxide, *Geochim. Cosmochim. Acta*, 12, 133–149, 1957.

Edmond, J. M.: High precision determination of titration alkalinity and total carbon dioxide content of sea water by potentiometric titration, *Deep-Sea Res.*, 17, 737–750, 1970.

Goericke, R. and Fry, B.: Variations of marine plankton $\delta^{13}\text{C}$ with latitude, temperature, and dissolved CO_2 in the world ocean, *Global Biogeochem. Cy.*, 8, 85–90, 1994.

Gruber, N., Keeling, C. D., and Stocker, T. F.: Carbon-13 constraints on the seasonal inorganic carbon budget at the BATS site in the Northwestern Sargasso Sea, *Deep-Sea Res. I*, 45, 673–717, 1998.

Gruber, N., Keeling, C. D., Bacastow, R. B., Guenther, P. R., Lueker, T. J., Whalen, M., Meijer, H. A. J., Mook, W. G., and Stocker, T. F.: Spatiotemporal patterns of carbon-13 in the global surface oceans and the oceanic Suess effect, *Global Biogeochem. Cy.*, 13, 307–335, 1999.

Gruber, N. and Keeling, C. D.: Seasonal carbon cycling in the Sargasso Sea near Bermuda, *Scripps Inst. Oceanogr.*, 30, 96 pp., 1999.

Keeling, R. F., Piper, S. C., Bollenbacher, A. F., and Walker, S. J.: Monthly atmospheric $^{13}\text{C}/^{12}\text{C}$ isotopic ratios for 11 SIO stations. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, USA, 2010.

Kroopnick, P.: Correlations between ^{13}C and ΣCO_2 in surface waters and atmospheric CO_2 , *Earth Planet. Sci. Lett.*, 22, 397–403, 1974.

McNeil, B., Matear, R., and Tilbrook, B.: Does carbon 13 track anthropogenic CO_2 in Southern ocean. *Global Biogeochem. Cy.*, 15, 597–613, 2001.

McNeil, B. and Tilbrook, B.: A seasonal carbon budget for the sub-antarctic Ocean, South of Australia, *Mar.Chem.*, 115, 196–210, 2009.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Metzl, N., Corbière, A., Reverdin, G., Lenton, A., Takahashi, T., Olsen, A., Johannessen, T., Pierrot, D., Wanninkhof, R., Ólafsdóttir, S. R., Olafsson, J., and Ramonet, M.: Recent acceleration of the sea surface fCO_2 growth rate in the North Atlantic Subpolar Gyre (1993–2008) revealed by winter observations, *Global Biogeochem. Cy.*, 24, 1–13, doi:10.1029/2009GB003658, 2010.

Olafsson, J., Olafsdottir, S. R., Benoit-Cattin, A., and Takahashi, T.: The Irminger Sea and the Iceland sea time series measurements of sea water carbon and nutrient chemistry 1983–2008, *Earth Syst. Sci. Data*, 2, 99–104, 2010, <http://www.earth-syst-sci-data.net/2/99/2010/>.

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 Ólafsdóttir, S. R.: Magnitude and origin of the anthropogenic CO_2 increase and Suess effect in the Nordic seas since 1981, *Global Biogeochem. Cy.*, 20, 1–12, doi:10.1029/2005GB002669, 2006.

Quay, P. D. and Stutsman, J.: Surface layer carbon budget for the subtropical N. Pacific: $\delta^{13}\text{C}$ constraints at station ALOHA, *Deep-Sea Res. I*, 50, 1045–1061, 2003.

Quay, P. D., Tilbrook, B., and Wong, C.: Oceanic uptake of fossil fuel CO_2 : Carbon-13 evidence, *Science*, 256, 74–79, 1992.

Quay, P. D., Sonnerup, R., Westby, T., Stutsman, J., and McNichol, A.: Changes in the $^{13}\text{C}/^{12}\text{C}$ of dissolved inorganic carbon in the ocean as a tracer of anthropogenic CO_2 uptake, *Global Biogeochem. Cy.*, 17, 1004, doi:10.1029/2001GB001817, 2003.

Quay, P. D., Sonnerup, R., Stutsman, J., Maurer, J., Körtzinger, A., Padin, X. A., and Robinson, C.: Anthropogenic CO_2 accumulation rates in the North Atlantic Ocean from changes in the $^{13}\text{C}/^{12}\text{C}$ of dissolved inorganic carbon, *Global Biogeochem. Cy.*, 21, 1–15, doi:10.1029/2006GB002761, 2007.

Racapé, V., Lo Monaco, C., Metzl, N., and Pierre, C.: Summer and winter distribution of $\delta^{13}\text{C}_{\text{DIC}}$ in surface waters of the South Indian Ocean (20°S – 60°S), *Tellus B*, 62, 660–673, doi:10.1111/j.1600-0889.2010.00504.x, 2010.

Raitsos, D. E., Lavender, S. J., Pradhan, Y., Tyrell, T., Reid, P. C., and Edwards, M.: Coccolithophore bloom size variation in response to the regional environment of the subarctic North Atlantic, *Limnol. Oceanogr.*, 51, 2122–2130, 2006.

Racapé, V., Pierre, C., Metzl, N., Lo Monaco, C., Reverdin, G., Olsen, A., Morin, P., Ríos, A. F., Vázquez-Rodríguez, M., and Pérez, F. F.: Anthropogenic carbon changes in the Irminger

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Basin (1981–2006): Coupling $\delta^{13}\text{C}_{\text{DIC}}$ and DIC observations, *J. Mar. Syst.*, 62, 660–673, doi:10.1016/j.jmarsys.2012.12.005, 2013.

Sonnerup, R. E. and Quay, P. D.: ^{13}C constraints on ocean carbon cycle models, *Global Biogeochem. Cy.*, 26, GB2014, doi:10.1029/2010GB003980, 2012

5 Tagliabue, A. and Bopp, L.: Towards understanding global variability in ocean carbon-13, *Global Biogeochem. Cy.*, 22, GB1025, doi:10.1029/2007GB003037, 2008.

Takahashi, T., Olafsson, J., Goddard, J. G., Chipman, D. W., and Sutherland, S. C.: Seasonal variations of CO_2 and nutrients in the high latitude surface oceans: a comparative study, *Global Biogeochem. Cy.*, 7, 843–878, 1993

10 Ullman, D.J., Galen, A. McKinley, G. A., Bennington, V., and Dutkiewicz, S.: Trends in the North Atlantic carbon sink: 1992–2006, *Global Biogeochem. Cy.*, 23, GB4011, doi:10.1029/2008GB003383, 2009

15 Vangriesheim A., Pierre, C., Aminot A., Metzl, N., Baurand, F., and Caprais, J-C.: The influence of Congo river discharges in the surface and deep layers of the Gulf of Guinea. *Deep-Sea Res. II*, 56, 2183–2196, doi:10.1016/j.dsr2.2009.04.002, 2009.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Table 1. Summary of sampling periods conducted on board the merchant vessels Skogafoss and Reykjafoss between Reykjavik (64° N, Iceland) and Newfoundland (47° N, Canada) over the period 2005–2012. The average values of $\delta^{13}\text{C}_{\text{DIC}}$ and DIC as well as their standard deviation (std) were estimated for the interior of the North Atlantic SubPolar Gyre (NASPG 53–62° N).

	NASPG (53–62° N)				
	Date	n_{tot} (‰)	Mean $\delta^{13}\text{C}_{\text{DIC}} \pm \text{std}$ ($\mu\text{mol kg}^{-1}$)	Mean DIC $\pm \text{std}$	n
<i>M/V Skogafoss</i>					
	23–27 Jul 2005	30	1.65 ± 0.10	2077.4 ± 10.0	15
	17–24 Sep 2005	23	1.46 ± 0.11	2089.9 ± 9.3	8
	12–16 Nov 2005	21	1.06 ± 0.07	2120.7 ± 10.6	16
	7–11 Feb 2006	34	0.87 ± 0.05	2142.4 ± 4.5	20
	18–28 Apr 2006	32	0.90 ± 0.09	2137.7 ± 8.5	12
	25–27 Jun 2006	22	1.64 ± 0.08	2058.7 ± 8.4	4
	11–15 Nov 2006	22	0.99 ± 0.12	2114.3 ± 11.6	13
<i>M/V Reykjafoss</i>					
	21–25 Aug 2010	30	1.36 ± 0.11	2054.4 ± 9.9	23
	15–19 Dec 2010	24	0.97 ± 0.10	2114.6 ± 7.6	13
	13–18 Mar 2011	22	0.66 ± 0.08	2149.4 ± 5.9	15
	16–20 Dec 2011	26	0.69 ± 0.05	2150.6 ± 4.1	23
	11–13 Mar 2012	26	0.61 ± 0.04	2152.5 ± 2.4	13
	30 Jun to 04 Jul 2012	22	1.28 ± 0.09	2089.7 ± 9.1	11
	21 to 25 Sep 2012	27	1.33 ± 0.12	2095.7 ± 13.5	13

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Table 2. Seasonal amplitude of $\delta^{13}\text{C}_{\text{DIC}}$ ($\Delta\delta^{13}\text{C}_{\text{DIC}}$) and their standard deviation (std). The biological and physical contributions ($\Delta\delta^{13}\text{C}_{\text{bio}}$ and $\delta^{13}\text{C}_{\text{phy}}$ respectively) for climatological cycle and anomalies were estimated from the Eqs. (4) and (5).

		$\Delta\delta^{13}\text{C}_{\text{DIC}} \pm \text{std} (\text{‰})$	$\Delta\delta^{13}\text{C}_{\text{bio}} \pm \text{std} (\text{‰})$	$\delta^{13}\text{C}_{\text{phy}} \pm \text{std} (\text{‰})$
Climatological seasonal cycle				
WINTER	to SUMMER	0.77 ± 0.07	0.74 ± 0.12	0.03 ± 0.14
Anomalies				
Summer 2005	to Nov 2006	-0.65 ± 0.14	-0.42 ± 0.10	-0.23 ± 0.15
Mar 2010	to Aug 2010	NA	1.00 ± 0.10	NA
Aug 2010	to Dec 2010	-0.44 ± 0.09	-0.61 ± 0.11	0.18 ± 0.11

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

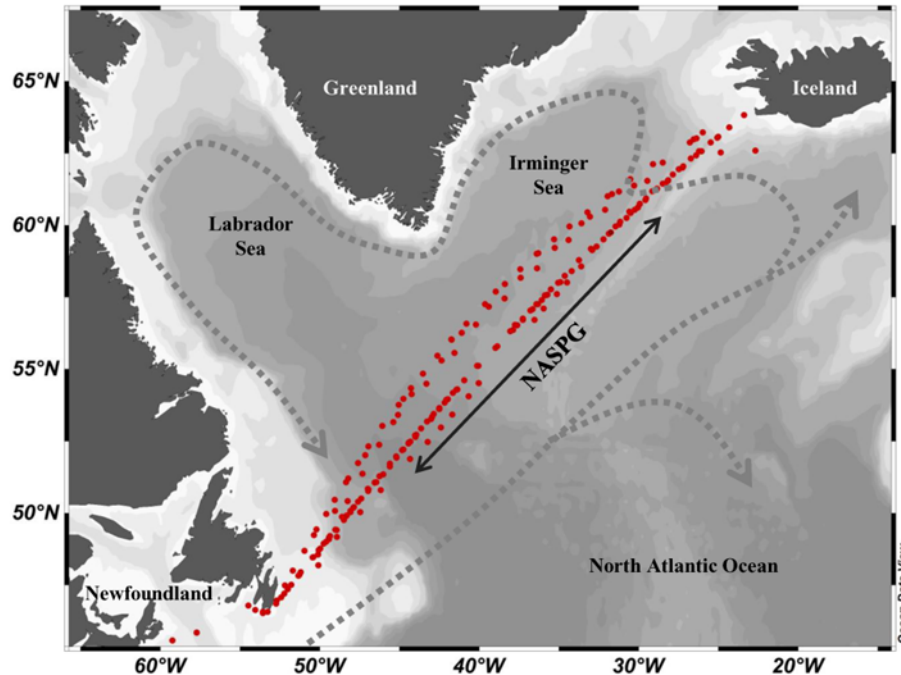


Fig. 1. Cruises track where $\delta^{13}\text{C}_{\text{DIC}}$ was sampled over the period 2005–2012 (red dots). Dashed lines indicate schematically main currents in the North Atlantic Ocean. The interior of the North Atlantic SubPolar Gyre (NASPG, 53–62°N), our study area, is delimited by the black arrows.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

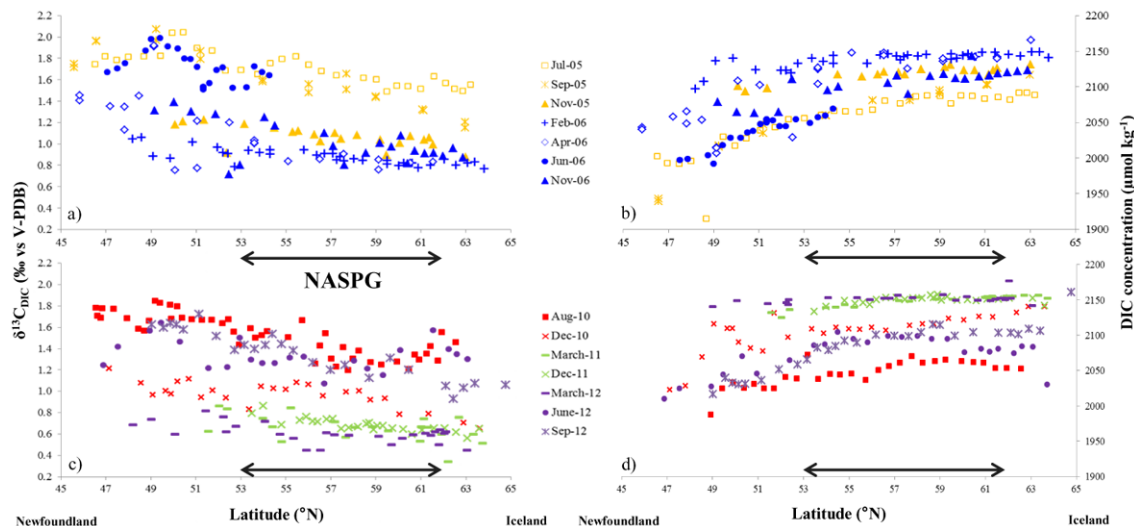


Fig. 2. Surface distribution of **(a–c)** $\delta^{13}\text{C}_{\text{DIC}}$ and **(b–d)** DIC concentration between Reykjavik (Iceland, 64° N) and Newfoundland (Canada, 47° N) over the period 2005–2006 **(a–c)** and 2010–2012 **(b–d)**. The interior of the North Atlantic SubPolar Gyre (NASPG, 53–62° N), our study area, is delimited by the black arrows.

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

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

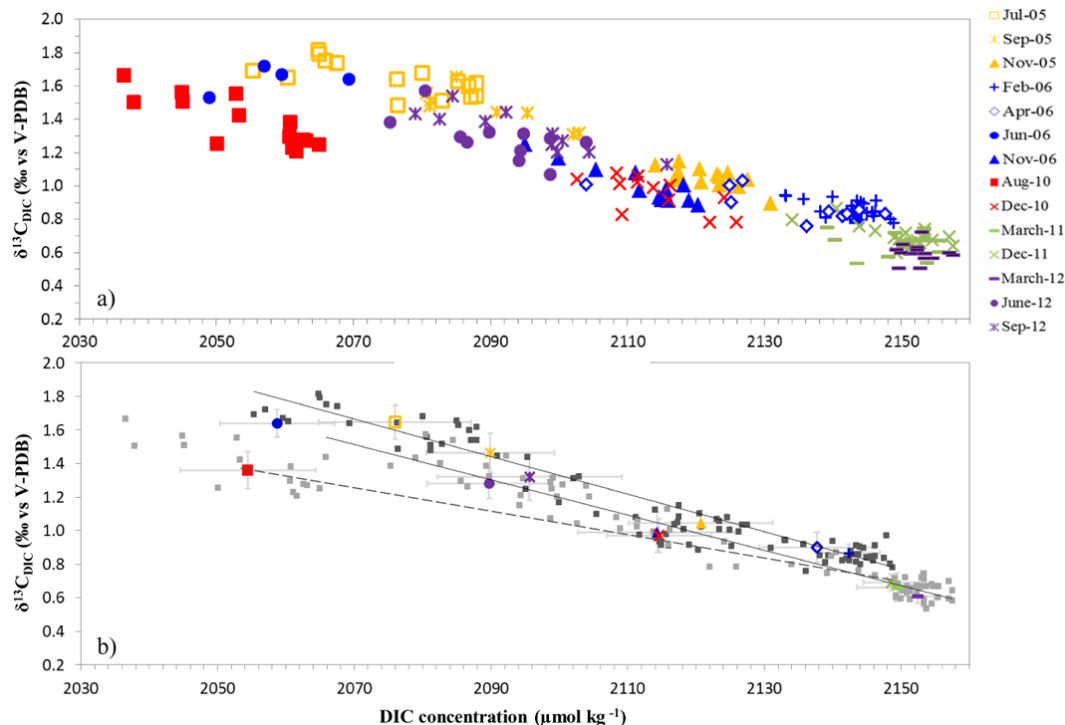


Fig. 3. (a), (b) $\delta^{13}\text{C}_{\text{DIC}}$ vs. Dissolved Inorganic Carbon (DIC) concentration collected in the surface waters of the North Atlantic SubPolar Gyre (NASPG, 53–62° N) between 2005 and 2012. **(b)** Dark grey squares represent 2005–2006 data set whereas light grey squares symbolize the 2010–2012 data set. The linear regressions indicated with dark lines were estimated for the periods from July 2005 to April 2006 and from March 2011 to September 2012 (from the bottom up: $y = -0.0108x + 23.81, r^2 = 0.95$ and $y = -0.0112x + 24.869, r^2 = 0.95$) and with dashed line was estimated for the period from August 2010 to March 2011 ($y = -0.007x + 16.58, r^2 = 0.94$). Mean values (and standard deviation) of $\delta^{13}\text{C}_{\text{DIC}}$ and DIC concentration for each data set are shown with colored symbols following the legend of Fig. 3a.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

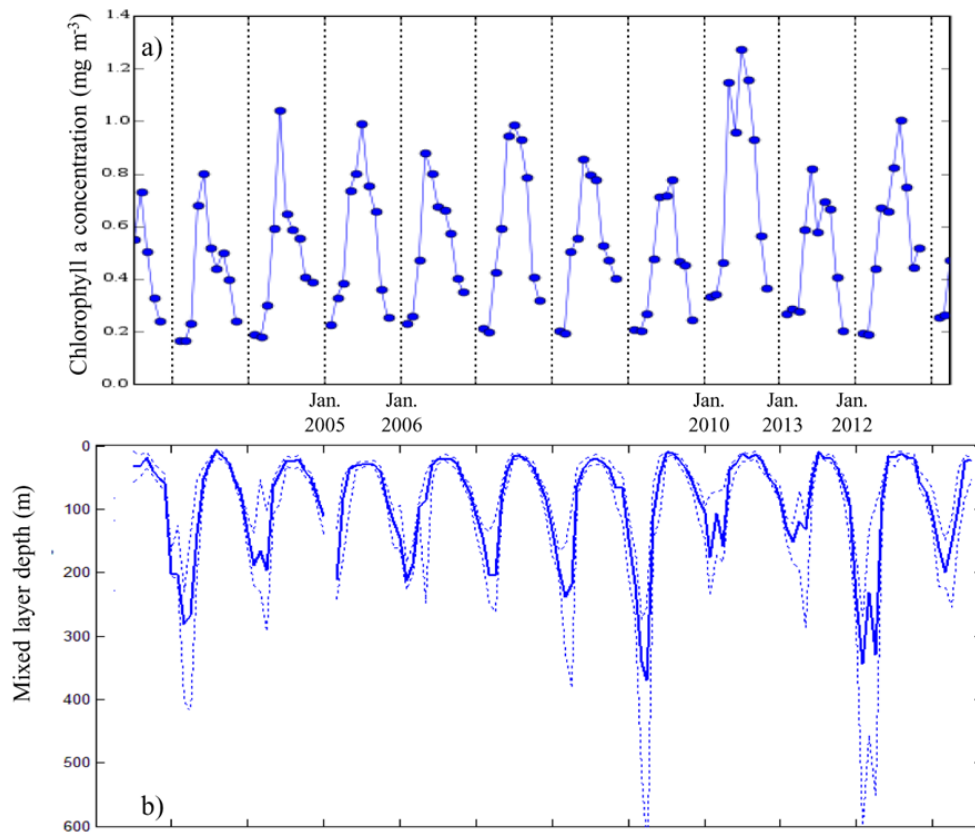


Fig. 4. Distribution of **(a)** Chlorophyll *a* concentration from MODIS-Aqua 4 km (disc.sci.gsfc.nasa.gov/giovanni, time series generated between 44–27°W and 53–62°N) and of **(b)** mixed layer depth (MLD, m) from Argo-float observations in NASPG. The MLD is estimated on each profile as the depth at which temperature deviates by 0.1°C from the temperature at 5 m. The full line represents the median depth whereas the dashed lines correspond to the first and third quartiles.

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

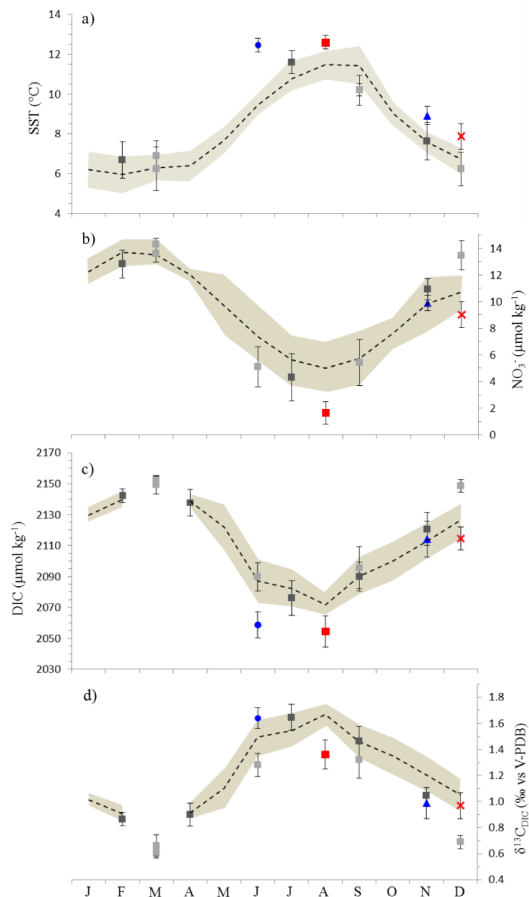


Fig. 5. Caption on next page.

The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The seasonal cycle of $\delta^{13}\text{C}_{\text{DIC}}$ in the North Atlantic Subpolar Gyre

V. Racapé et al.

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

Fig. 5. Mean seasonal cycle of **(a)** Sea Surface Temperature (SST), **(b)** nitrate (NO_3^-), **(c)** Dissolved Inorganic Carbon (DIC), and **(d)** $\delta^{13}\text{C}_{\text{DIC}}$ in the surface waters of the NASPG (53–62° N). Light grey squares (and standard deviation) symbolize the 2010–2012 data set whereas dark grey squares (and standard deviation) represent the 2005–2006 data set. Black dashed curves and their standard deviation were established from **(a)** MODIS-aqua data set recorded in 2005–2006 (monthly composite with a spatial resolution of 9 km, generated by NASA's Giovanni, disc.sci.gsfc.nasa.gov/giovanni), **(b)** and **(c)** both NO_3^- and DIC measurements collected during SURATLANT cruises between 2002 and 2006 and **(c)** from 2005–2006 $\delta^{13}\text{C}_{\text{DIC}}$ -DIC relationship presented in Fig. 3b. Anomalies are identified by colored symbols following the legend of Fig. 3a.