Temporal and spatial trends in marine carbon isotopes in the Arctic Ocean and implications for food web studies

Trends in carbon isotopes in the Arctic Ocean

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Abstract:

The Arctic is undergoing unprecedented environmental change. Rapid warming, decline in sea ice extent, increase in riverine input, ocean acidification and changes in primary productivity are creating a crucible for multiple concurrent environmental stressors, with unknown consequences for the entire arctic ecosystem. Here, we synthesised 30 years of data on the stable carbon isotope (δ\(^{13}\)C) signatures in dissolved inorganic carbon (δ\(^{13}\)C-DIC; 1977 to 2014), marine and riverine particulate organic carbon (δ\(^{13}\)C-POC; 1986 to 2013) and tissues of marine mammals in the Arctic. δ\(^{13}\)C values in consumers can change as a result of environmentally driven variation in the δ\(^{13}\)C values at the base of the food web or alteration in the trophic structure, thus providing a method to assess the sensitivity of food webs to environmental change. Our synthesis reveals a spatially heterogeneous and temporally evolving δ\(^{13}\)C baseline, with spatial gradients in the δ\(^{13}\)C-POC values between arctic shelves and arctic basins likely driven by differences in productivity and riverine and coastal influence. We report a decline in δ\(^{13}\)C-DIC values (-0.011 ‰ yr\(^{-1}\)) in the Arctic, reflecting increasing anthropogenic carbon dioxide (CO\(_2\)) in the Arctic Ocean (i.e. Suess effect), which is larger than predicted. The larger decline in δ\(^{13}\)C-POC values and δ\(^{13}\)C in arctic marine mammals reflects the anthropogenic CO\(_2\) signal as well as the influence of a changing arctic environment. Combining the influence of changing sea ice conditions and isotopic fractionation by phytoplankton, we explain the decadal decline in δ\(^{13}\)C-POC values in the Arctic Ocean and partially explain the δ\(^{13}\)C values in marine mammals with consideration of time-varying integration of δ\(^{13}\)C values. The response of the arctic ecosystem to ongoing environmental change is stronger than we would predict theoretically, which has tremendous implications for the study of food webs in the rapidly changing Arctic Ocean.
Introduction

The Arctic is changing rapidly (IPCC, 2013), warming twice as fast as the global average (Carmack et al., 2015; Hoegh-Guldberg & Bruno, 2010), causing sea ice to decline in both extent and thickness (Kwok, 2018; Lind, Ingvaldsen, & Furevik, 2018). Sea ice underpins the entire arctic ecosystem and the decline in this seasonal habitat is affecting the entire food web. Primary production has increased by 30% from 1998 to 2012 owing to an increase in light under reduced ice conditions (Arrigo & van Dijken, 2015). Arctic predators, such as seals and polar bears, that rely on sea ice for foraging, moulting and breeding are also adversely affected by the loss of sea ice (Laidre et al., 2008). Other climate-induced changes are occurring in tandem and include acidification (Yamamoto, Kawamiya, Ishida, Yamanaka, & Watanabe, 2012), shifts in wind patterns and enhanced wind-field in the Western Arctic (Overland & Wang, 2010), increased coastal erosion, river flow and melting of permafrost and glaciers (Haine et al., 2015; Jones et al., 2009; Mars & Houseknecht, 2007). These multiple concurrent stressors have far-reaching implications for the arctic marine ecosystem at multiple trophic levels, and there is an urgent need to understand the ecosystem response in this unique polar habitat.

The ratio of stable carbon isotopes, $^{13}$C and $^{12}$C, expressed as $\delta^{13}$C ($\permil$), provides a powerful tool for studying food webs. The $\delta^{13}$C values of particulate organic carbon (POC), consisting of fresh phytoplankton, microzooplankton, bacteria and marine and terrestrial detritus, (Fry & Sherr, 1989; Lobbes, Fitznar, & Kattner, 2000; Michener & Kaufman, 2007; Wassmann et al., 2004), represent the base of the food web or “baseline”. The $\delta^{13}$C values of POC ($\delta^{13}$C-POC) are generally transferred with a $^{13}$C enrichment of 1 to 2 $\permil$ between each trophic level, creating an inextricable link between the base of the food web and consumers (Fry, Anderson, Entzeroth, Bird, & Parker, 1984). Spatial trends in $\delta^{13}$C-POC values controlled by environmental factors have been used to decipher the foraging and migratory
patterns of consumers on a regional scale (Hoffman, 2016; Iken, Bluhm, & Dunton, 2010; Polito et al., 2017; Wassenaar, 2019) and more recently on a global scale in the construction of global ‘isoscape’ (Bird et al., 2018; Bowen & West, 2008; Firmin, 2016; Graham, Koch, Newsome, McMahon, & Aurioles, 2010; McMahon, Hamady, & Thorrold, 2013b). However, spatial and temporal trends in the $\delta^{13}$C values of high trophic levels may also reflect changes in food web structure such as loss or addition of species, consumer’s diet, or a combination of factors. To disentangle the drivers of spatial and temporal trends in the $\delta^{13}$C values of consumers in the Arctic, it is crucial to establish spatial and temporal variations in $\delta^{13}$C values at the base of the food web, allowing the sensitivity of marine arctic consumers to environmental change to be quantified.

It is challenging to isolate phytoplankton-POC for analysis and so the nominal definition of $\delta^{13}$C-POC values typically assumes that the bulk of POC is derived from phytoplankton only, although $\delta^{13}$C-POC values can be influenced by other factors such as bacterial activity and detritus (Michener & Kaufman, 2007). While the detrital fraction of POC may be degraded by bacteria, potentially altering the $\delta^{13}$C values of that fraction, we assume that photosynthetic phytoplankton are responsible for transforming the bulk of $\delta^{13}$C-POC values in time and space. $\delta^{13}$C value of phytoplankton, which underpins the $\delta^{13}$C-POC values is controlled by fractionation during photosynthesis. This equates to the difference between the $\delta^{13}$C values of the carbon source, either dissolved inorganic carbon (DIC) or carbon dioxide (CO$_2$) and the $\delta^{13}$C-POC values (Cassar, Laws, Bidigare, & Popp, 2004; Young, Bruggeman, Rickaby, Erez, & Conte, 2013). Factors such as phytoplankton growth rate, availability or concentration of carbon, light and nutrient availability affect isotopic fractionation and the $\delta^{13}$C-POC values (Burkhardt, Riebesell, & Zondervan, 1999; Keeley & Sandquist, 1992). As such, environmental conditions can create distinct patterns in these values. $\delta^{13}$C-POC values become enriched in $^{13}$C in an environment where replenishment of

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the CO₂ pool is slow or restricted, for example during periods of rapid phytoplankton growth (Rau, Takahashi, Des Marais, Repeta, & Martin, 1992) or in sea ice associated with sympagic primary production (Budge et al., 2008; Hobson et al., 2002; Søreide et al., 2013; Wang, Budge, Gradinger, Iken, & Wooller, 2014). Conversely, an increase in CO₂ concentration will lead to a carbon pool depleted in ¹³C (Rau et al., 1992) creating a ¹³C-deplete POC pool. Terrestrially derived POC delivered via rivers and coastal erosion also tends to be depleted in ¹³C relative to marine derived POC (Boutton, 1991; Keeley & Sandquist, 1992). While global isoscapes capture the large-scale spatial trends in δ¹³C values related to oceanographic provinces (shelf versus open ocean) and latitude (Bird et al., 2018; Bowen & West, 2008; Graham et al., 2010; McMahon et al., 2013b), they do not include the Arctic Ocean. We expect the δ¹³C values of POC in the Arctic to be influenced by the strong regional trends in sea ice, productivity and terrestrial influence including riverine input and coastal erosion, all of which vary along the water mass circulation pathways from the inflow shelves, which receive water from the Atlantic and Pacific oceans, to the arctic basins and interior shelves (Sakshaug, 2004; Tremblay & Gagnon, 2009; Varela, Crawford, Wrohan, Wyatt, & Carmack, 2013).

Imprinted on the regional trends is a temporal trend in δ¹³C values worldwide. Enhanced atmospheric CO₂ since the industrial period (Tagliabue & Bopp, 2008) is causing an increase in oceanic CO₂ (Sabine et al., 2004) and a decline in the δ¹³C values of DIC (δ¹³C-DIC), known as the Suess effect, as a result of ¹³C-depleted anthropogenic CO₂ (Quay, Sonnerup, Westby, Stutsman, & McNichol, 2003). δ¹³C-DIC values in the Arctic Ocean are predicted to change at a rate of −0.006 to −0.008 ‰ yr⁻¹, compared to the global average of −0.017 ‰ yr⁻¹ (Tagliabue & Bopp, 2008). However, several studies have already shown that decadal trends in the δ¹³C values of marine mammals in the Arctic (Misarti, Finney, Maschner, & Wooller, 2009; Nelson, Quakenbush, Mahoney, Taras, & Wooller, 2018; Nelson, Quakenbush, Mahoney, Taras, & Wooller, 2018; Nelson, Quakenbush, Mahoney, Taras, & Wooller, 2018).
Newsome et al., 2007; Schell, 2001) are larger than the Suess effect alone, implying that other factors are altering their $\delta^{13}$C signatures on decadal time scales.

The main objective of this study was to quantify how regional differences and temporal trends in the arctic environment have altered the $\delta^{13}$C values in DIC and POC, representing the base of the food web or “baseline”. We compared these trends at the base of the food web to trends in $\delta^{13}$C values in arctic marine mammals to investigate how environmental change (e.g. Suess effect, loss of sea ice) may alter $\delta^{13}$C values in the entire food web. We synthesised published data from 1977 to 2014 on $\delta^{13}$C values of DIC and dissolved CO$_2$, and $\delta^{13}$C-POC values in the surface ocean (POC$_{\text{water}}$) and in sea ice (POC$_{\text{ice}}$) across the entire Arctic Ocean, alongside data from arctic rivers (POC$_{\text{riv}}$). We quantified regional differences in the $\delta^{13}$C values in POC and discuss the underlying environmental drivers of the observed spatial heterogeneity. We then quantified the decadal trends in $\delta^{13}$C values of DIC and CO$_2$, and $\delta^{13}$C values of POC in the Arctic Ocean, comparing the rate of change to the Suess effect and observed trends in tissues of arctic marine mammals from the post-industrial period.

Material and Methods

Data collation

Data on bulk $\delta^{13}$C-POC$_{\text{water}}$, $\delta^{13}$C-POC$_{\text{ice}}$ and $\delta^{13}$C-POC$_{\text{riv}}$ values, focusing on suspended particulate organic matter above the thermocline, were collated from tables and figures in 37 original manuscripts and two open access data bases for both marine (PANGAEA; http://www.pangaea.de) and riverine (articGRO; https://arcticgreatrivers.org/) environments, in Arctic and sub-Arctic regions, as defined by the Köppen-Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). The database included 354 data points for marine $\delta^{13}$C-POC$_{\text{water}}$ values (Brown et al., 2014; Connelly, McClelland,
Crump, Kellogg, & Dunton, 2015; Forest et al., 2010; Griffith et al., 2012; Guo, Tanaka, Wang, Tanaka, & Murata, 2004; Hallanger et al., 2011; Hobson, Ambrose, & Renaud, 1995; Hobson et al., 2002; Iken et al., 2010; Iken, Bluhm, & Gradinger, 2005; Ivanov, Lein, Zakharova, & Savvichev, 2012; Kohlbach et al., 2016; Kuliński, Kędra, Legeżyńska, Gluchowska, & Zaborska, 2014; Kuzyk, Macdonald, Tremblay, & Stern, 2010; Lin et al., 2014; Lovvorn et al., 2005; O’Brien, Macdonald, Melling, & Iseki, 2006; Parsons et al., 1989; Roy et al., 2015; Sarà et al., 2007; Schubert & Calvert, 2001; Smith, Henrichs, & Rho, 2002; Søreide et al., 2008; Søreide, Hop, Carroll, Falk-Petersen, & Hegseth, 2006; Tamelander, Reigstad, Hop, & Ratkova, 2009; Tamelander et al., 2006; Tremblay, Michel, Hobson, Gosselin, & Price, 2006; Zhang et al., 2012), 69 data points for δ\(^{13}\)C-POC\(_{\text{ice}}\) values (Forest et al., 2010; Hobson et al., 1995; Hobson et al., 2002; Iken et al., 2005; Kohlbach et al., 2016; Lovvorn et al., 2005; Roy et al., 2015; Schubert & Calvert, 2001; Søreide et al., 2008; Søreide et al., 2006; Tamelander et al., 2006; Tremblay et al., 2006) and 383 data points for riverine δ\(^{13}\)C-POC\(_{\text{riv}}\) values (Goni, Yunker, Macdonald, & Eglinton, 2000; Holmes, McClelland, Tank, Spencer, & Shiklomanov, 2018; Kuzyk et al., 2010; Lobbes et al., 2000).

Data was available over different temporal scales: marine δ\(^{13}\)C-POC\(_{\text{water}}\) values from 1986 to 2013, δ\(^{13}\)C-POC\(_{\text{ice}}\) from 1993 to 2012, and riverine δ\(^{13}\)C-POC\(_{\text{riv}}\) values from 1987 to 2016.

To relate the temporal trend in δ\(^{13}\)C-POC\(_{\text{water}}\) values to the predicted decline of δ\(^{13}\)C-DIC and δ\(^{13}\)C-CO\(_2\) values, a compilation of data on δ\(^{13}\)C-DIC values was extracted from three publications (Bauch, Polyak, & Ortiz, 2015; Schmittner et al., 2013; Young et al., 2013) and two databases (Becker et al., 2016; Key et al., 2015). δ\(^{13}\)C-CO\(_2\) values were determined from the δ\(^{13}\)C-DIC values and absolute temperature following the equation E1 (Rau, Riebesell, & Wolf-Gladrow, 1996). δ\(^{13}\)C-DIC and δ\(^{13}\)C-CO\(_2\) values included 1333 data points covering years from 1977 to 2014.

\[
\delta^{13}\text{C-CO}_2 = \delta^{13}\text{C-DIC} + 23.644 - 9701.5 \div T \ (E1)
\]

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where \( T \) = temperature in Kelvin.

To determine if the temporal trend in \( \delta^{13}\text{C-POC} \) values was reflected in higher trophic levels within the Arctic Ocean, \( \delta^{13}\text{C} \) data were collated from arctic marine mammals covering years following the industrial period (post 1950). We collated \( \delta^{13}\text{C} \) data from teeth of ringed seals (\textit{Pusa hispida}) from 1986 to 2006 from East Greenland (Aubail, Dietz, Rigét, Simon-Bouhet, & Caurant, 2010) and northern fur seals (\textit{Callorhinus ursinus}) from 1950 to 2000 from the Bering Sea and Gulf of Alaska (Newsome et al., 2007). Additionally, \( \delta^{13}\text{C} \) data were collated from teeth of Beluga whales (\textit{Delphinapterus leucas}) from 1963 to 2008 from the Hudson Bay and from 1976 to 2001 from the Baffin Bay (Matthews & Ferguson, 2018), and baleen plates of bowhead whales (\textit{Balaena mysticetus}) from 1950 to 1998 from the Bering and Chukchi Seas (Schell, 2001).

\textit{Data treatment}

We analysed the \( \delta^{13}\text{C-POC}_{\text{water}} \), \( \delta^{13}\text{C-POC}_{\text{ice}} \), \( \delta^{13}\text{C-DIC} \) and \( \delta^{13}\text{C-CO}_2 \) values in seventeen marine arctic regions (Figure 1, Table 1). In addition, the \( \delta^{13}\text{C-POC}_{\text{water}} \) values from arctic rivers were grouped into two large riverine regions: the Siberian rivers and the North American rivers (Figure 1, Table 1). The regions were defined based on their location, and physical and biological characteristics. Most of the data was collected in summer and \( \delta^{13}\text{C-POC}_{\text{water}} \) did not vary seasonally (S1). In order to achieve the best spatial coverage, data from all seasons and years were combined for the spatial comparison. Regional means were calculated for \( \delta^{13}\text{C-POC}_{\text{water}} \), \( \delta^{13}\text{C-POC}_{\text{ice}} \), \( \delta^{13}\text{C-POC}_{\text{riv}} \), \( \delta^{13}\text{C-DIC} \) and \( \delta^{13}\text{C-CO}_2 \) values (Table 1).

The decadal variation of regional marine \( \delta^{13}\text{C-POC}_{\text{water}} \) values in arctic regions was assessed where data was available for at least three different years covering a period of at least five years. This included the following regions: arctic basins, Beaufort Sea, Chukchi Sea...
and Bering Sea. Svalbard and the Barents Sea, which had similar \( \delta^{13}C \)-POC\textsubscript{water} values and \( \delta^{13}C \)-POC\textsubscript{ice} values (S2: ANOVA3 and 4), were combined into the ‘European Arctic’ to achieve the best temporal coverage. The mean decadal trend (all regions combined) was calculated for \( \delta^{13}C \)-POC\textsubscript{water}, \( \delta^{13}C \)-POC\textsubscript{ice}, \( \delta^{13}C \)-DIC and \( \delta^{13}C \)-CO\textsubscript{2} values.

**Statistical analyses**

Quantile-Quantile plots of the residuals were plotted to check how closely the data follow a normal distribution (Becker, Chambers, & Wilks, 1988). The data was normally distributed and therefore we used a one way ANOVA \((\alpha = 0.005)\) (Zuur, Ieno, & Smith, 2007) followed by post hoc Tukey pairwise comparison tests in R (R Core Team, 2018) to spatially compare: 1) the \( \delta^{13}C \)-POC\textsubscript{water} data between arctic shelves and arctic basins (ANOVA1), between arctic shelves and arctic rivers (ANOVA2), and between all arctic shelves (ANOVA3); and 2) the \( \delta^{13}C \)-POC\textsubscript{ice} values between all marine arctic regions where data were available (ANOVA4). We used a two ways ANOVA followed by post hoc Tukey pairwise comparison test to compare the \( \delta^{13}C \)-POC\textsubscript{ice} values with \( \delta^{13}C \)-POC\textsubscript{water} values (factor “origin”) for regions (factor “region”) where both data sets were available (ANOVA5). Arctic regions with less than five data points were excluded from statistical analyses. Relevant p-values of the post hoc Tukey pairwise comparison tests following ANOVA1 to 5 are shown in S2.

We applied linear models in R (R Core Team, 2018) to quantitatively assess the latitudinal gradient in \( \delta^{13}C \)-DIC, \( \delta^{13}C \)-CO\textsubscript{2} and \( \delta^{13}C \)-POC\textsubscript{water} values, and the temporal trends in \( \delta^{13}C \) values of marine POC\textsubscript{water}, POC\textsubscript{ice}, DIC, dissolved CO\textsubscript{2} and arctic marine mammals. The significance and robustness of the linear models were assessed based on the p-values of the slopes and intercepts, the \( R^2 \), the F-values and degree of freedom (S3) (Zuur et al., 2007).
Results

Spatial trends in the δ\textsuperscript{13}C of the baseline

The Atlantic and Pacific waters entering the Arctic via the South Iceland and Norwegian Sea, and Gulf of Alaska and Bering Sea, respectively (Figure 1, Table 1), had similar δ\textsuperscript{13}C-CO\textsubscript{2} values and were depleted by up to 2 % relative to the δ\textsuperscript{13}C-CO\textsubscript{2} values in the arctic basins (Table 1). We observed a significant depletion in δ\textsuperscript{13}C-CO\textsubscript{2} and δ\textsuperscript{13}C-POC\textsubscript{water} values with increasing latitude (Figure 2). δ\textsuperscript{13}C-DIC did not vary with latitude (Figure 2a).

We analysed the δ\textsuperscript{13}C-POC\textsubscript{water}, δ\textsuperscript{13}C-POC\textsubscript{ice} and δ\textsuperscript{13}C-CO\textsubscript{2} values in seventeen marine arctic regions (Figure 1, Table 1). δ\textsuperscript{13}C values of POC\textsubscript{water} varied significantly between arctic regions (Figure 3a). POC\textsubscript{water} from arctic shelves was significantly enriched in 13C compared to POC\textsubscript{water} from arctic basins and POC\textsubscript{riv} (Figure 3a, S\textsuperscript{2}: ANOVA1 and 2). The δ\textsuperscript{13}C-POC\textsubscript{water} values was 13C depleted in arctic shelves (Beaufort Sea, Svalbard fjords, Canadian archipelago and the Hudson Bay) influenced by fresh water (Table 1, Figure 1) relative to the inflow (Chukchi Sea and Barents Sea) shelves and the North Water Polynya (Figure 3a; S\textsuperscript{2}: ANOVA3).

δ\textsuperscript{13}C-POC\textsubscript{ice} values followed the same regional trend as δ\textsuperscript{13}C-POC\textsubscript{water} values, with δ\textsuperscript{13}C-POC\textsubscript{ice} values enriched in 13C in the inflow and outflow shelves (Barents Sea, North Water Polynya) compared to the interior shelf Beaufort Sea and the arctic basins (Figure 3b; S\textsuperscript{2}: ANOVA4).

Comparison between δ\textsuperscript{13}C of POC\textsubscript{ice} and POC\textsubscript{water}

Generally, δ\textsuperscript{13}C values of POC\textsubscript{ice} were significantly 13C-enriched compared to those of POC\textsubscript{water} (p < 0.005; S\textsuperscript{2}: ANOVA5), with δ\textsuperscript{13}C-POC\textsubscript{water} being enriched by 4.4 % in the Barents Sea, by 4.2 % in the North Water Polynya and by 7.0 % in the Canadian archipelago.
(Table 1). There were no significant differences between POC_{ice} and POC_{water} in the Svalbard region, the arctic basins and the Beaufort Sea (S2: ANOVA5). δ^{13}C-POC_{ice} values was highly variable in most of the arctic regions (Figure 3b).

**Temporal trends in the δ^{13}C of the baseline and Arctic marine mammals**

In all arctic regions combined, δ^{13}C-DIC (1977-2014), δ^{13}C-CO\textsubscript{2} (1977-2014) and δ^{13}C-POC\textsubscript{water} (1986-2013) values became significantly 13C depleted by 0.011 ± 0.001 ‰ yr\textsuperscript{-1}, 0.011 ± 0.002 ‰ yr\textsuperscript{-1} and 0.149 ± 0.020 ‰ yr\textsuperscript{-1} respectively (Figure 4a; Table 2). The temporal trends in δ^{13}C-POC\textsubscript{water} values were statistically significant in the Beaufort Sea (−0.117 ± 0.033 ‰ yr\textsuperscript{-1}; 1987-2013) and in the arctic basins (−0.256 ± 0.057 ‰ yr\textsuperscript{-1}; 1997-2012) and not statistically significant in the European Arctic, Bering Sea and Chukchi Sea (Figure 4b; Table 2, S3). The temporal trend in δ^{13}C-POC\textsubscript{ice} values were not significant (Figure 4d; Table 2, S3). The δ^{13}C values in the teeth of northern fur seals, ringed seals and beluga whales, and in baleen plates of bowhead whales were significantly depleted in 13C with time (Figure 4c; Table 2). The decline in δ^{13}C values in teeth ranged from 0.020 ± 0.003 ‰ yr\textsuperscript{-1} in northern fur seals from the Gulf of Alaska (1950-2000) to −0.046 ± 0.012 ‰ yr\textsuperscript{-1} in Ringed seals from East Greenland (1986-2006; Table 2). The δ^{13}C in the baleen plates of bowhead whales from the Bering and Chukchi Seas significantly decreased by 0.064 ± 0.010‰ yr\textsuperscript{-1} (1965-1998; Table 2). The decline in δ^{13}C values of POC\textsubscript{water} and marine mammals was larger than decline in δ^{13}C-DIC and δ^{13}C-CO\textsubscript{2} values (0.011 ‰ yr\textsuperscript{-1}, this study). Details of the linear models are shown in S3.

**Discussion**

**Ice versus water**

The 13C-enrichment in POC\textsubscript{ice} compared to POC\textsubscript{water} in arctic regions has been observed previously and attributed to carbon limitation around ice algae within sea ice (Budge et al., 2008; Hobson et al., 2002; Søreide et al., 2006; Wang et al., 2014). The termination of the spring ice-edge bloom can cause 13C at the base of the food web to be
altered when $^{13}$C-enriched ice-algae are added to $^{13}$C-depleted pelagic phytoplankton (Søreide et al., 2006). The similarity in the $\delta^{13}$C-POC$_{\text{ice}}$ and $\delta^{13}$C-POC$_{\text{water}}$ values in some regions (see section 2.2.) and the high intra-regional variability of the $\delta^{13}$C-POC$_{\text{ice}}$ values may be explained by differences in ice porosity, allowing replenishment of DIC from water to ice (Thomas & Papadimitriou, 2011). $\delta^{13}$C-POC$_{\text{ice}}$ values were likely to have been influenced by light availability and the high bacterial activity in sea ice compared to open water (Wang et al., 2014). Thus, variation in the sampling month for sea ice might also contribute to the high variability in $\delta^{13}$C-POC$_{\text{ice}}$. This highlights that caution is required when using bulk $\delta^{13}$C values of POC$_{\text{ice}}$ and POC$_{\text{water}}$ to distinguish between open water versus ice dependent food webs in the Arctic (Søreide et al., 2006). The challenge of disentangling the contribution of carbon derived from sympagic production to the food web was successfully resolved by using compound specific stable isotope analyses (e.g. $\delta^{13}$C values of fatty acids; Graham, Oxtoby, Wang, Budge, and Wooller (2014); Oxtoby, Budge, Iken, Brien, and Wooller (2016); Oxtoby et al. (2017); Wang et al. (2015)).

*Spatial trends*

Spatial trends in the $\delta^{13}$C values of POC$_{\text{water}}$ and POC$_{\text{ice}}$ were similar, implying that they were influenced by the same environmental drivers within specific regions of the Arctic Ocean.

Low temperature, high wind speed and high productivity enhance the atmospheric CO$_2$ uptake by the Arctic Ocean (Takahashi et al., 2002), driving strong latitudinal gradients in concentration and $\delta^{13}$C values of oceanic CO$_2$ with $^{13}$C-CO$_2$ being more depleted in the Arctic Ocean ($\approx -10\%o$ (Young et al., 2013) and $-10.2 \pm 0.5 \%o$, this study) relative to the tropics ($\approx -7 \%o$) (Young et al., 2013). In the marine environment, more than 90% of DIC is composed of bicarbonate ions (HCO$_3^-$; Boutton (1991). Fractionation between HCO$_3^-$ and atmospheric
CO$_2$ increases in cold water (Zhang, Quay, & Wilbur, 1995) leading to $^{13}$C enrichment of $\delta^{13}$C-DIC values with increasing latitude (Tagliabue & Bopp, 2008), as observed in this study (Figure 2a). $\delta^{13}$C-POC$_{\text{water}}$ values became $^{13}$C-depleted with increasing latitude (Figure 2b, this study) (Goericke & Fry, 1994; McMahon et al., 2013b), reflecting the latitudinal trend in $\delta^{13}$C-CO$_2$ values as well as multiple additional factors, including temperature, phytoplankton growth rates, bacterial activity and isotopic fractionation, that also vary with latitude (Fouilland et al., 2018; Thomas, Kremer, Klausmeier, & Litchman, 2012; Young et al., 2013). A latitudinal trend in $\delta^{13}$C values of zooplankton was observed in the western Arctic (i.e. Bering and Chukchi Sea) (Dunton, Saupe, Golikov, Schell, & Schonberg, 1989), demonstrating the transfer of this $\delta^{13}$C signature to the next trophic level.

The two orders of magnitude difference in phytoplankton production between the nutrient rich arctic shelves and the ice covered nutrient depleted arctic basin (Sakshaug, 2004) may partially explain the relatively large difference in $\delta^{13}$C-POC$_{\text{water}}$ values of 2.3 ‰ between the arctic shelf (-24.0 ± 1.2 ‰) and arctic basins (-26.3 ± 1.6 ‰). High rates of primary production cause $^{13}$C enrichment of the $\delta^{13}$C-POC values (Boutton, 1991; McMahon, Hamady, & Thorrold, 2013a). The highly productive Bering Sea and Barents Sea account for up to two thirds of the total arctic phytoplankton production (Sakshaug, 2004). Advection of nutrients from the arctic outflow and early exposure to sunlight enhance phytoplankton productivity in the North Water Polynya (Sakshaug, 2004). In contrast, high turbidity and strong stratification caused by fresh water inflow from rivers onto the interior shelves reduce light and restrict phytoplankton production (Dittmar & Kattner, 2003). Lower phytoplankton productivity in the river influenced Beaufort Sea and Siberian Coast, as well as the Northeast Water Polynya (Sakshaug, 2004) could explain the depleted $\delta^{13}$C-POC values observed in these regions relative to the more productive regions.
The $^{13}$C depletion in $\delta^{13}$C-POC_{water} values observed in the interior shelves, Svalbard fjords, Hudson Bay and Canadian archipelago compared to other arctic shelf regions likely reflects the contribution of $^{13}$C-depleted terrestrially derived POC (Boutton, 1991) from rivers, coastal erosion and glacial streams. Seventy-two arctic rivers supplying 40% of the total freshwater input from the surrounding continents of Eurasia and North America enter the Arctic Ocean via the interior shelves of the Siberian coast and the Beaufort Sea (Table 1, Figure 1) at a rate of 2500 to 4200 km$^3$ yr$^{-1}$ (Haine et al., 2015). In addition, terrestrially derived POC input resulting from coastal erosion may be equal to or larger than input from river discharge in some regions, for instance along the Siberian coast (Rachold et al., 2000). Finally, glacial fjords on Svalbard are fed with freshwater by large glaciers and streams with the highest freshwater inflow in summer during ice and snow melt (Cottier et al., 2005). Any temporal alteration of the riverine inputs or the drainage basins would likely alter the $\delta^{13}$C-POC_{water} values in the interior shelves and subsequently alter the base of the food web.

**Temporal trends at the baseline**

The increasing concentration of anthropogenic CO$_2$, known as the Suess effect, is predicted to decrease the oceanic $\delta^{13}$C-DIC values by an average of 0.017 ‰ yr$^{-1}$, with high spatial variability from 0 ‰ yr$^{-1}$ in the Southern Ocean to 0.024 ‰ yr$^{-1}$ in the subtropical gyres (Tagliabue & Bopp, 2008). In the Arctic Ocean, the $\delta^{13}$C-DIC values are predicted to decrease by 0.006 ‰ to 0.008 ‰ yr$^{-1}$ (Tagliabue & Bopp, 2008). We observed a decreasing trend in $\delta^{13}$C-DIC values of 0.011 ± 0.001 ‰ yr$^{-1}$ from 1977 to 2014 across all arctic regions, which is larger than the predicted trend. Although CO$_2$ represents less than 0.5 % of the total DIC pool, it is the only component that is exchangeable with the atmosphere. In polar regions, especially the Arctic Ocean, the decline in sea ice has led to an expansion of open water (Arrigo & van Dijken, 2015). This facilitates atmospheric exchange and enhances the
dissolved CO₂ concentration (Yamamoto et al., 2012) resulting in an additional ¹³C depletion of δ¹³C-CO₂ values (Rau et al., 1992) which may explain the larger decrease in δ¹³C-CO₂ values (0.011 ± 0.002 ‰ yr⁻¹) and in turn the larger decrease in δ¹³C-DIC values (0.011 ± 0.001 ‰ yr⁻¹) in the Arctic Ocean compared to the predicted decrease of 0.006 to 0.008 ‰ yr⁻¹ (Tagliabue & Bopp, 2008).

The decadal decline in δ¹³C-POC_water values (1987 to 2013) was more than ten times larger than the trend in δ¹³C values of CO₂ (or DIC) implying that other factors are influencing the δ¹³C values in POC in the Arctic Ocean. Since the mid-1990s, sea ice extent has declined by 8.3 ± 0.6 ‰ per decade across the entire Arctic (Comiso, 2012). Sea ice algae are up to 7 ‰ enriched in ¹³C relative to pelagic phytoplankton (this study) and a decline in sea ice could decrease the contribution of ice algal biomass to total productivity and reduce the total mean δ¹³C values of POC_water. For example, the open water area of the Barents sea has increased by 15,789 km² or 1.3 ‰ per year between 1998 to 2012, alongside a 28 ‰ increase in net primary production over the same time period (Arrigo & van Dijken, 2015). Assuming distinct end members for δ¹³C-POC_water (−25.0 ± 1.7 ‰) and δ¹³C-POC_ice (−20.0 ± 1.3 ‰) values, sea ice decline would cause the entire pool of δ¹³C-POC values to decrease by 0.06 ± 0.15 ‰ per year. Additionally, the photosynthetic isotopic fractionation factor for phytoplankton in the Arctic Ocean has increased by 0.045 ‰ yr⁻¹ since the 1960s, compared to a global average of 0.022 ‰ yr⁻¹ (Young et al., 2013). The combined effect of a decline in ice algae (0.06 ± 0.15 ‰ yr⁻¹, this study), increase in fractionation factor (0.045 ‰ yr⁻¹) (Young et al., 2013) and Suess effect (i.e. dissolved CO₂, 0.011 ± 0.001 ‰ yr⁻¹, this study) could potentially cause the δ¹³C-POC values to decrease by 0.116 ± 0.15 ‰ per year, which is of the same order of magnitude as the observed annual decrease in δ¹³C-POC_water values in the whole Arctic (0.149 ± 0.028 ‰ yr⁻¹) and in the Beaufort Sea (0.126 ± 0.020 ‰ yr⁻¹; Table 2). In support of this argument, the difference between the temporal trend or slope in

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\[ {\delta^{13}C}_{\text{CO}_2} \text{ and } {\delta^{13}C}_{\text{POC}} \text{ values (Figure 4a) increased by } 0.138 \pm 0.028 \text{ \text{‰ yr}^{-1}} \text{ in agreement with the sum of the contributions from a change in ice (0.06 \pm 0.15 \text{ \text{‰ yr}^{-1}}), fractionation (0.045 \text{ \text{‰ yr}^{-1}}), and Suess effect (0.011 \pm 0.001 \text{ \text{‰ yr}^{-1}}) influencing } {\delta^{13}C}_{\text{POC}_{\text{water}}} \text{ values.} \]

Other factors contributing to the decline in \[ {\delta^{13}C}_{\text{POC}} \text{ values in the Arctic Ocean include } \text{river run-off, coastal erosion, primary production and bacterial activity. Increased riverine runoff (Haine et al., 2015) and costal erosion (Jones et al., 2009; Mars & Houseknecht, 2007) resulting from ongoing climate change in the Arctic could contribute to the decline in } {\delta^{13}C}_{\text{POC}} \text{ values by adding } ^{13}\text{C-deplete terrestrial material to the marine POC pool. Changes in primary productivity will also influence the } {\delta^{13}C}_{\text{POC}} \text{ values. For example, the decline of } {\delta^{13}C} \text{ values in Bowhead whales from the Bering/Chukchi Sea was interpreted by Schell (2000) as reflecting a 30 to 40\% decrease in seasonal primary productivity in the Bering Sea over the last 30 years. Increasing bacterial activity with increasing temperature (Vaqué et al., 2019; Vernet, Richardson, Metfies, Nöthig, & Peeken, 2017) and dissolved CO}_2 \text{ concentration (Grossart, Allgaier, Passow, & Riebesell, 2006) in the Arctic may also influence the } {\delta^{13}C} \text{ values of POC.} \]

**Implications for food web**

The reliability of stable carbon isotopes in deciphering the provenance of feeding or migratory patterns of consumers is heavily dependent on knowledge of \[ {\delta^{13}C} \text{ values at the base of the food web. Maps that convey the geographical and temporal trends of } {\delta^{13}C} \text{ values in the baseline, termed isoscapes (Bowen et al., 2009; Graham et al., 2010), have become a necessity for interpreting trophic structure using } {\delta^{13}C} \text{ (or } {\delta^{15}N} \text{) values (Hansen, Hedeholm, Sünkser, Christensen, & Grønkjær, 2012; Newsome, Clementz, & Koch, 2010). Although isoscapes have been constructed for the atmosphere (Bowen et al., 2009), terrestrial environment (Bowen & West, 2008; Firmin, 2016) and the Atlantic and Pacific Oceans,
(Graham et al., 2010; McMahon et al., 2013b), this study provides a first view of $\delta^{13}$C-POC values or carbon isoscape of the Arctic Ocean. We found spatially heterogeneous and temporally evolving $\delta^{13}$C values in the POC pool, which has ramifications for the study of food webs in space and time.

Previous studies have noted that the decline in $\delta^{13}$C in Arctic marine mammals is larger than the Suess effect alone (e.g. Matthews and Ferguson (2018); Newsome et al. (2007)), but the lack of $\delta^{13}$C baseline information prevented these authors from disentangling the driving factors (Cullen, Rosenthal, & Falkowski, 2001; Schell, 2000, 2001). Generally, the temporal decline in the $\delta^{13}$C values in marine mammals was larger than in $\delta^{13}$C-DIC and $\delta^{13}$C-CO$_2$ values (both of $-0.011 \pm 0.001$ ‰ yr$^{-1}$) but smaller than the decline observed in $\delta^{13}$C-POC$_{\text{water}}$ values ($-0.149 \pm 0.028$ ‰ yr$^{-1}$). The $\delta^{13}$C signature in phytoplankton or a consumer represents an average ratio related to the life time of the organism and tissue turnover time (Vander Zanden, Clayton, Moody, Solomon, & Weidel, 2015). Previous studies have shown that the seasonal variation in $\delta^{13}$C values of POC was higher than in higher trophic levels reflecting the strong seasonal growth cycle of phytoplankton and shorter time period over which they integrate carbon (O’reilly, Hecky, Cohen, & Plisnier, 2002). In contrast, consumers from zooplankton to predators are long lived and thus integrate $\delta^{13}$C values over their seasonal foraging and migratory routes (Aubail et al., 2010; Schell, Saupe, & Haubenstock, 1989) with the time of integration depending on the tissue type (Vander Zanden et al., 2015) or the animals lifetime (O’reilly et al., 2002). The effect of yearly averaging of the $\delta^{13}$C values in marine mammal teeth and baleen plates used to reconstruct decadal trends may have reduced the larger, short-lived variation observed in $\delta^{13}$C-POC values mainly representing summer in this study. The gradual linear decline in $\delta^{13}$C values in arctic seals and whales likely reflects alterations to the $\delta^{13}$C-POC values. A change in diet, for example a shift towards foraging closer to freshwater (Nelson et al., 2018), or more
pelagic feeding habits (Aubail et al., 2010), may also contribute to the temporal decline in δ¹³C values observed in predators.

This study demonstrates that to disentangle factors driving variation in the δ¹³C values in a consumer, it is vital to know the spatial heterogeneity and temporal evolution of δ¹³C values of the baseline in the Arctic Ocean in order to avoid inaccurate interpretation of changes in food web structures. Some studies have attempted to correct the δ¹³C values in arctic marine mammals for the Suess effect using modelled and predicted values for large geographical regions, prior to interpreting decadal trends in δ¹³C values (Carroll, Horstmann-Dehn, & Norcross, 2013; Misarti et al., 2009; Nelson et al., 2018). However, the Suess effect varies spatially (Tagliaabue & Bopp, 2008) and therefore local values should be used for this correction. For example, the Suess effect in the Arctic Ocean (0.011 ± 0.001 ‰ yr⁻¹, this study) differs from the predicted modelled values (0.006 to 0.008 ‰ yr⁻¹ ;Tagliaabue and Bopp (2008)), implying that other factors, such as the loss of sea ice, are accelerating the influence of anthropogenic CO₂ in the Arctic. In addition, the decline in δ¹³C-POC values, representing the base of the food web, is larger than the decline in δ¹³C-DIC values (this study). This suggests that interpretation about diet shift should be done after consideration of temporal trends in δ¹³C-POC values and not only in δ¹³C-DIC (Suess effect). These results also highlight the importance of considering time-averaging effects when studying different trophic levels and/or tissues having respectively variable life and turnover times. Insight from this study has direct implications for how we interpret changes in δ¹³C values in consumers, especially in environments experiencing rapid change.
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Table 1: Location and description of marine regions and rivers, and regional means ± standard deviation of δ¹³C values in dissolved inorganic carbon (DIC), ocean dissolved CO₂, POC-water, POC-ice and POC-riv.

| Marine regions | Description | Regional mean ± standard deviation (n=number of observations) | References |
|----------------|-------------|-------------------------------------------------------------|------------|
|                |             | δ¹³C-DIC (%) | δ¹³C-CO₂ (%) | δ¹³C-POC-water (%) | δ¹³C-POC-ice (%) | (Becker et al., 2016; Key et al., 2015; Sarà et al., 2007; Schmittner et al., 2013; Young et al., 2013) |
| Outer shelves  |             |             |             |                     |                     |                                      |
| South Iceland  | Atlantic influenced | 1.3 ± 0.2 (n=560) | -9.3 ± 0.2 (n=560) | -19.9 ± 3.3 (n=4) | NA | (Becker et al., 2016; Key et al., 2015; Sarà et al., 2007; Schmittner et al., 2013; Young et al., 2013) |
| Norwegian sea  | Atlantic influenced | 1.4 ± 0.4 (n=183) | -10.0 ± 0.4 (n=183) | NA | NA | (Bauch et al., 2015; Becker et al., 2016; Key et al., 2015) |
| Hudson Bay     | Atlantic influenced: fresh water influenced | NA | NA | -24.7 ± 1.3 (n=19) | NA | (Kurzyk et al., 2010) |
| Bering sea     | Pacific influenced | 1.3 ± 0.6 (n=11) | -9.8 ± 0.8 (n=11) | -23.9 ± 0.7 (n=62) | -21.5 ± 0.9 (n=2) | (Guo et al., 2004; Lin et al., 2014; Lovvorn et al., 2005; Schmittner et al., 2013; Smith et al., 2002; Young et al., 2013; Zhang et al., 2012) |
| Gulf of Alaska | Pacific influenced | 0.8 ± 0.2 (n=50) | -10.3 ± 0.3 (n=50) | NA | NA | (Schmittner et al., 2013; Young et al., 2013) |
| Inflow shelves |             |             |             |                     |                     |                                      |
| Barents sea    | Atlantic influenced | 1.0 ± 0.4 (n=10) | -10.3 ± 0.5 (n=10) | -23.7 ± 1.6 (n=12) | -19.3 ± 2.6 (n=12) | (Becker et al., 2016; Søreide et al., 2006; Tamelander et al., 2009; Tamelander et al., 2006) |
| Svalbard       | Northwest of the Barents sea inflow shelf | 1.3 ± 0.4 (n=17) | -10.0 ± 0.4 (n=17) | -24.5 ± 0.9 (n=12) | -23.0 ± 0.7 (n=6) | (Becker et al., 2016; Søreide et al., 2008; Søreide et al., 2006; Tamelander et al., 2009) |
| Chukchi sea    | Pacific influenced | 0.8 ± 0.5 (n=21) | -10.8 ± 0.7 (n=21) | -22.7 ± 0.1 (n=36) | NA | (Bauch et al., 2015; Iken et al., 2010; Ivanov et al., 2012; Zhang et al., 2012) |
| Interior shelves |             |             |             |                     |                     |                                      |
| Siberian coast | Fresh water influenced; consists of the East Siberian sea | NA | NA | -24.5 ± 0.5 (n=7) | NA | (Iken et al., 2010; Ivanov et al., 2012) |
| Beaufort sea   | Fresh water influenced; North American coast | NA | NA | -26.7 ± 2.2 (n=43) | -26.4 ± 0.5 (n=8) | (Connelly et al., 2015; Forest et al., 2010; Iken et al., 2005; O'Brien et al., 2006; Parsons et al., 1989; Zhang et al., 2012) |
| Outflow shelves |             |             |             |                     |                     |                                      |
| Fram strait    | Northeast of Greenland | 1.3 ± 0.4 (n=102) | -10.5 ± 0.4 (n=102) | NA | NA | (Bauch et al., 2015; Becker et al., 2016) |
| Northeast water polynya | Recurring mesoscale areas of open water within areas of pack ice (Sakshaug, 2004; Northeast of Greenland) | NA | NA | -27.7 ± 0.6 (n=3) | -18.6 ± 0.2 (n=3) | (Hobson et al., 1995) |
| North water polynya | Recurring mesoscale areas of open water within areas of pack ice (Sakshaug, 2004; North Baffin bay | NA | NA | -21.9 ± 0.6 (n=30) | -17.7 ± 3.5 (n=20) | (Hobson et al., 2002; Tremblay et al., 2006) |
| Canadian archipelago | Complex straits and channels, terrestrial influence | NA | NA | -25.9 ± 1.4 (n=21) | -18.9 ± 2.3 (n=9) | (Roy et al., 2015) |
| Arctic basins  | Includes Amundsen, Nansen and Canadian basins | 1.0 ± 0.2 (n=134) | -11.1 ± 0.2 (n=134) | -26.3 ± 1.6 (n=88) | -22.1 ± 2.4 (n=9) | (Bauch et al., 2015; Brown et al., 2014; Griffiths et al., 2012; Ivanov et al., 2012; Kohlbach et al., 2016; Schubert & Calvert, 2001; Søreide et al., 2006; Tamelander et al., 2009; Zhang et al., 2012) |
| Riverine regions | Description | δ¹³C-POC-riv (%) | References |
| Siberian rivers | Includes the large rivers of Lena, Ob and Yenisey and smaller rivers of Kolyma, Indigirka, Yana, Olenek, Yakima and Mezen | NA | NA | -29.5 ± 2.1 (n=237) | NA | (Holmes et al., 2018; Lobbes et al., 2000) |
| North American rivers | Consists of the large rivers of Mackenzie and Yukon, as well as the smaller rivers surrounded the Hudson Bay (Figure 1) | NA | NA | -29.5 ± 1.7 (n=146) | NA | (Goni et al., 2000; Holmes et al., 2018; Kurzyk et al., 2010) |

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Table 2: Slopes ± standard deviation and p-values of the decadal linear models of δ\textsuperscript{13}C values in dissolved inorganic carbon (DIC), ocean dissolved CO\textsubscript{2}, POC\textsubscript{water}, POC\textsubscript{ice} and arctic marine mammal tissues; Lines in bold are considered significant (p < 0.005). Detailed statistics of the linear models are shown in S3.

|                          | Slope ± standard deviation | p-value | Time period     | Number of observations |
|--------------------------|-----------------------------|---------|-----------------|------------------------|
| POC\textsubscript{water} |                             |         |                 |                        |
| Beaufort sea             | -0.117 ± 0.033              | <0.005  | 1987-2013       | 71                     |
| European Arctic          | -0.499 ± 0.265,             | 0.076   | 1999-2004       | 20                     |
| Arctic basins            | -0.256 ± 0.057              | <0.005  | 1997-2012       | 87                     |
| Bering sea               | -0.019 ± 0.046              | 0.679   | 1998-2010       | 62                     |
| Chukchi sea              | +0.008 ± 0.071              | 0.906   | 2003-2009       | 36                     |
| All data                 | -0.149 ± 0.020              | <0.005  | 1987-2013       | 311                    |
| POC\textsubscript{ice}  |                             |         |                 |                        |
| All data                 | -0.185 ± 0.106              | 0.084   | 1993-2012       | 69                     |
| DIC                      |                             |         |                 |                        |
| All data                 | -0.011 ± 0.001              | <0.005  | 1977-2014       | 1333                   |
| CO\textsubscript{2}      |                             |         |                 |                        |
| All data                 | -0.011 ± 0.002              | <0.005  | 1977-2014       | 1333                   |
| Marine mammals           |                             |         |                 |                        |
| Northern fur seal        | -0.020 ± 0.003              | <0.005  | 1950-2000       | 40                     |
| Ringed seal              | -0.046 ± 0.012              | <0.005  | 1986-2006       | 36                     |
| Beluga whale –Hudson Bay | -0.026 ± 0.003              | <0.005  | 1963-2008       | 42                     |
| Beluga whale – Baffin Bay| -0.021 ± 0.006              | <0.005  | 1976-2001       | 26                     |
| Bowhead whale – Bering sea/Chukchi sea | -0.064 ± 0.007 | <0.005 | 1965-1998 | 34 |
Figure captions:

Figure 1: Map indicating the locations of the arctic regions considered in this study; Circulation pathways are highlighted and modified from Carmack and Wassmann (2006); The yellow arrows represent the intermediate Pacific water and the red arrows represent the Atlantic water; White arrows indicate the mouths of the arctic rivers; The black circles point to the approximate location of the North water polynya in the Northern Baffin bay, Northeast water polynya in Northeast Greenland, and Svalbard marine coastal area; Chu. = Churchill River, Nel. = Nelson River, Hay. = Hayes River, Win. = Winisk River, Gr.Wh. = Great Whale River, Li.Wh. = Little Whale River, Nas. = Nastapoca River, Inn. = Innuksuac River; Bathymetry and coast lines were from the software Ocean Data View (Schlitzer, 2016).

Figure 2: Stable carbon isotope values (δ¹³C, in ‰) of (a) marine dissolved inorganic carbon (DIC) (n = 1333) and marine dissolved CO₂ (n = 1333) and (b) marine POC_water (n = 354) in the surface waters with latitude; each dot is a single data point; the solid line represents the slope of the linear regression; dashed lines indicate the 95% confidence interval of the linear regression. The equations and p-values of the linear regressions are shown on the figure. Trends are considered significant when p < 0.005.

Figure 3: Regional stable carbon isotope values (δ¹³C, in ‰) of (a) POC_water and POC_riv and (b) POC_ice; Numbers of observations are shown as number on top of the boxplots. Results of post hoc Tukey tests following (a) ANOVA1 to ANOVA3 and (b) ANOVA4 are expressed as letters on top of the boxplots. Different letters indicate significant differences (p < 0.005) between regions. The p-values of each test are shown in S2.

Figure 4: Decadal trend in δ¹³C values of: (a) dissolved inorganic carbon (DIC), dissolved CO₂ and POC_water, (b) POC_water for each arctic region, (c) POC_water and arctic marine mammal tissues, and (d) POC_ice for each arctic region. BS = Bering sea, GA = Gulf of Alaska, EG = East Greenland, HB = Hudson bay, CS = Chukchi sea; Results of the linear models can be found in Table 2 and S3. Number of observations can be found in Table 2.
