Observing the Arctic Ocean carbon cycle in a changing environment

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Abstract

Climate warming is especially pronounced in the Arctic, which has led to decreased sea-ice coverage and substantial permafrost thawing. These changes have a profound impact on the carbon cycle that directly affects the air–sea exchange of carbon dioxide (CO_2), possibly leading to substantial feedback on atmospheric CO_2 concentration. Several recent studies have indicated such feedback but the future quantitative impact is very uncertain. To minimize these uncertainties, there is a need for extensive field studies in order to achieve both a better process understanding as well as to detect probable trends in these processes. In this contribution, we describe a number of processes that have been reported to be impacted by climate change and suggest a coordinated international observational programme for their study.

It is well known that the Arctic is undergoing rapid and substantial climate change, which has transformed the environment. The most obvious manifestation of change is the loss of permanent pack ice, which results in an ever shrinking summer sea-ice coverage (Cavalieri et al. 1996; Stroeve et al. 2012), but the thawing of the permafrost in the Arctic Ocean's drainage basins is equally striking (e.g., Lawrence & Slater 2005). Many other more subtle shifts in the environment have occurred, like more melt-ponds, earlier melting, loss of snow cover, higher water temperatures on the shelves in the summer and warmer inflowing waters from the Atlantic and Pacific (e.g., Serreze et al. 2000; Shimada et al. 2006; Dmitrenko et al. 2008; Palmer et al. 2014). All of these changes can potentially alter the transformation and fluxes of carbon in large parts of the Arctic Ocean.

Primary production likely shifts in strength and location as a result of changes in light regimes and nutrient supply as the summer sea-ice coverage decreases. Increased wind-induced upwelling at the shelf break during sea-ice-free conditions has been suggested to be an important factor for supply of nutrients to the photic zone (Carmack & Chapman 2003). To what degree changes in primary production will translate into a higher sedimentation rate of organic matter into the deep waters is not obvious, even if substantial accumulation of ice algae at the sediment floor has been reported (Boetius et al. 2013). An increased primary production will have implications for the surface water partial pressure of carbon dioxide (pCO_2), which in turn can exchange with the atmosphere to a degree that is partly controlled by the sea-ice coverage. Furthermore, the Arctic Ocean carbon cycle is affected by surrounding land masses, for example, through increased input of organic matter from rivers and from coasts that are eroded as permafrost thaws (Vonk et al. 2014). The objective of this contribution is to suggest observation strategies for the study of potential transformations of the Arctic Ocean carbon cycle caused by variable processes, with the aim to better project future feedbacks to the climate system.

In any assessment of the Arctic Ocean's carbon cycle, it is essential to consider the oceanographic setting and therefore, especially, the water mass circulation (Fig. 1). Much of the water that enters the Arctic Ocean from the surrounding seas does so over large shelves. Inflowing waters from the Pacific Ocean pass through the large Bering and Chukchi seas before entering the deep central basins. Some water also flows west into the East Siberian Sea, while some flows to the east into the Beaufort Sea before exiting to the north. A portion of the water from
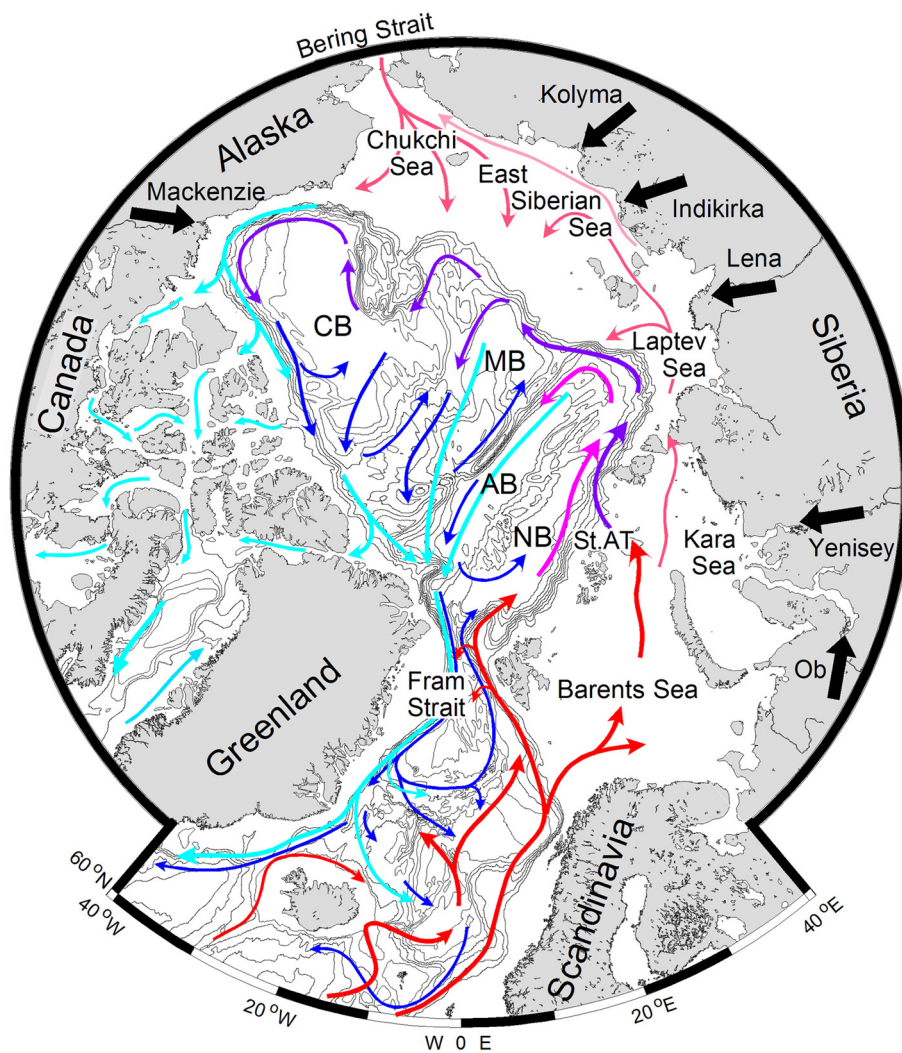
Fig. 1 Dominating Arctic Ocean currents with inflowing relative warms surface currents (red) and colder surface currents (light blue) together with intermediate and deep currents (burgundy and dark blue). Features of the Arctic Ocean are abbreviated as follows: Canadian Basin (CB), Makarov Basin (MB), Amundsen Basin (AB), Nansen Basin (NB) and St. Anna Trough (St.AT).

the Atlantic Ocean flows through the Barents Sea and exits through the St. Anna Trough into the deep central basin. A small quantity of Atlantic water flows into the Laptev Sea with an even smaller fraction making it all the way into the East Siberian Sea before flowing north into the central basins. During the transit over the shelves, substantial carbon transformation occurs, as described below.

The general circulation of the surface waters is largely determined by the dominating atmospheric pressure field that governs the wind patterns. Because these pressure fields vary on the decadal scale (e.g., the Arctic Oscillation), the front between the Pacific and Atlantic water in the East Siberian Sea can shift substantially (e.g., Johnson et al. 1999). In the central basins, some water

flows from the Siberian shelf seas towards Fram Strait in the so-called Transpolar Drift. Over the Canada Basin, the Beaufort Gyre dominates the large-scale circulation. The extents of both the Transpolar Drift and the Beaufort Gyre are also determined by the pressure field.

The oceanographic state together with the geographic conditions determine different biogeochemical regimes, with very high primary production in the inflow shelves, moderate to low primary production in the interior shelves and low primary production in the central Arctic Ocean (Carmack & Wassmann 2006). These conditions have a substantial impact on the carbon cycle of the Arctic Ocean. For instance, it has, up to the present, been shown that the Arctic Ocean surface waters are, for the most part, undersaturated with respect to carbon dioxide

(CO_2; Bates & Mathis 2009; Fransson et al. 2009; Jutterström & Anderson 2010). This has been attributed to cooling as well as primary production in the Barents and Bering–Chukchi seas (the inflow shelves) before the water enters the central regions where the sea-ice cover hampers air–sea exchange (Kaltin & Anderson 2004; Mathis et al. 2009). It is also in these marginal seas that primary production is high compared to the other Arctic shelf seas, as the inflowing waters constantly supply nutrients (Sakshaug 2004). In particular, the extraordinary supply of nutrients from the Pacific Ocean to the Bering and Chukchi seas supports productivity that is high in the global perspective, with new production of up to 160 gC m^{-2} yr^{-1} (Springer et al. 1996; Hill & Cota 2005).

The high productivity in the Chukchi Sea (bottom depth mostly less than 50 m) results in a relatively large supply of organic matter to the sediments, where much is microbially decayed, and the resulting chemical constituents released back to the bottom water (Fig. 2). Chukchi shelf-bottom water, often enriched by brine from sea-ice formation, flows off the shelf and into the central Arctic Ocean, where it produces an extensive water mass (the upper halocline) containing high nutrient, high CO_2 and low oxygen (Jones & Anderson 1986). Export of nutrient-rich water has also been shown to occur from the East Siberian Sea (e.g., Anderson et al. 2013) although primary production is not very high in this interior shelf sea. Even though the productivity of

the Barents Sea is substantial, the deeper depths, often more than 200 m, allow most of the organic matter to decay before reaching the seafloor (Slagstad & Wassmann 1996). Consequently, the decay products are spread over a greater salinity range and in a greater volume such that the dense waters leaving the Barents Sea contain a fainter chemical regeneration signature than the waters leaving the Chukchi Sea.

The export production of the central Arctic Ocean has, at least until recently, been very low (Anderson et al. 2003), and probably among the lowest in the global ocean (Honjo et al. 2010). The low level of new production in the central ocean is likely due to a weak supply of nutrients to interior surface water, because these tend to be consumed in the shelf seas. Added to this was the historically dense cover by permanent pack ice in the central Arctic Ocean, which may accumulate snow cover over several years, limiting the light needed for primary production. Of course, there is some productivity in the water column, as well as within the sea ice and by algae hanging from the sea ice (e.g., Wheeler et al. 1996; Krembs et al. 2011). However, the majority of this produced organic matter is not sedimented deep in the water column before becoming degraded by microbes (Honjo et al. 2010; O'Brien et al. 2013; Ericson et al. 2014) The near-absence of a labile particulate organic flux into the Arctic Ocean's basins is proven by the near constant concentrations of oxygen and nutrients in the water column from depths of a few hundred metres down to the bottom, nearly 4 km deep in
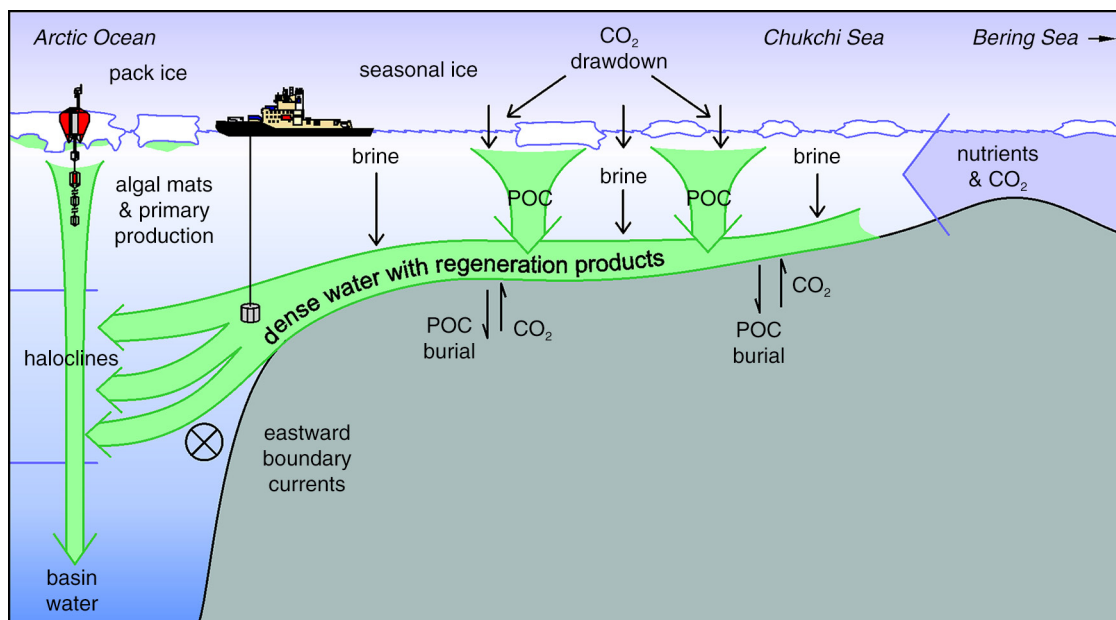

Fig. 2 Carbon transformation by marine primary production followed by sedimentation and microbial decay. In the shelf seas, much of the latter occurs at the sediment surface where brine-enriched water transport the decay products to the deep central basins. Particulate organic carbon is abbreviated to POC.

some places. For these waters, transient tracers give residence times of up to several hundred years at the greatest depths (Schlosser et al. 1994). Furthermore, the sediment accumulation rates in the central Arctic Ocean are predominantly on the order of a few millimetres per thousand years (Backman et al. 2004; Stein & Macdonald 2004).

An important way that the Arctic Ocean contributes to the global carbon cycle is through the uptake of anthropogenic CO_2. The cooling of the high-salinity waters flowing to the North along the Scandinavian coast results in a water that is dense enough to flow southward over the Scotland–Greenland ridge as a bottom current, making a major contribution to the start of the global conveyor belt (Mauritzen 1996). Also the high-salinity waters that are produced from the sea-ice brine, mainly in the polynyas distributed around the Arctic Ocean continental margin, create waters dense enough to contribute to this overflow (e.g., Jeansson et al. 2008). These intermediate and deep water formation processes build up the anthropogenic CO_2 concentration to a level that makes the Arctic Ocean inventory about twice as much on a per-volume basis as the global mean (Tanhua et al. 2009).

Processes likely to be impacted and approaches for their observation

Below, we emphasize several processes that will likely dominate future changes in the Arctic Ocean carbon cycle. As such, these processes contribute to the oceanic feedback within the climate system through interactions with the air–sea CO_2 exchange. We also suggest ways of observing shifts in carbon transformation and fluxes in the Arctic Ocean.

Thawing permafrost adds terrestrial organic matter to the shelf seas

The Arctic Ocean has a terrestrial drainage basin twice its own area, making this ocean one of the most "terrestrial" in the world in terms of both received freshwater runoff and organic carbon (Stein & Macdonald 2004). Furthermore, extensive land areas close to the coast of North America as well as most of Siberia contain vast amounts of terrigenous organic matter stored under permafrost conditions (McGuire et al. 2009), as do some areas of the continental shelves (Romanovskii et al. 2005; Vonk et al. 2012). Subaerial permafrost has an active upper zone that thaws during summer and freezes during winter. At the same time, many rivers, including five very large ones (Lena, Yenesey, Ob, Mackenzie and Yukon), along

with numerous small ones, drain these areas, with the largest discharge occurring during summer. Freshet delivers huge quantities of both dissolved and particulate organic matter into the Arctic shelf seas (Stein & Macdonald 2004; McGuire et al. 2009). Furthermore, coastal erosion adds particulate organic matter to the coastal zone in amounts matching the river loads (Stein & Macdonald 2004). The organic matter decays both in the rivers as well as in the shelf seas (Alling et al. 2010; Vonk et al. 2010), resulting in high pCO_2 in water partly isolated by stratification from immediate atmospheric exchange (e.g., Pipko et al. 2010). Likely most of the dissolved organic carbon (DOC), or coloured dissolved organic matter (CDOM), gets trapped at the surface by river-induced stratification, where much of it can become photolysed away, and the CO_2 is relatively free to exchange out into the atmosphere. In contrast, the particulate organic carbon (POC) sinks below the stratified surface layer where metabolism can then convert it to CO_2, which is trapped below by stratification.

With rising temperatures, more permafrost thaws, which potentially leads to intensified input of dissolved and particulate terrestrial organic matter to the shelf seas and further elevated pCO_2 levels (Fig. 3). Particulate carbon will likely derive from the release of old matter due to riverbank and coastal erosion, whereas DOC may be enhanced by altered vegetation and increased breakdown of organics in surface soils (Guo et al. 2007). In areas heavily impacted by the Lena River discharge, CO_2 supersaturation has been observed in the middle of summer even when all nutrients have been consumed by primary production (Anderson et al. 2009). Furthermore, decreasing sea-ice coverage over the shelves in late summer leads to later sea-ice formation in the coastal regions; the coasts are therefore more exposed to wave-induced erosion when fall storms hit, further amplifying the release of ancient organic matter to coastal seas (e.g., see Lantuit et al. 2012). If these processes leading to supersaturated waters escalate due to climate change, it would contribute a significant positive feedback considering that about 1700 Pg of organic carbon are presently stored in the Arctic's permafrost (Schuur et al. 2013).

Observational approaches for terrestrial organic matter. The Siberian shelves appear to offer the greatest potential to deliver substantial change through the processes described above. They receive much river discharge, have substantial coastal erosion, cover vast areas and are shallow (Fig. 3). Furthermore, these shelves have large terrigenous drainage basins that appear to be undergoing transition in their permafrost zones (e.g., Pokrovsky et al. 2012). Potential changes in the magnitude of terrestrial organic matter degradation must be investigated by
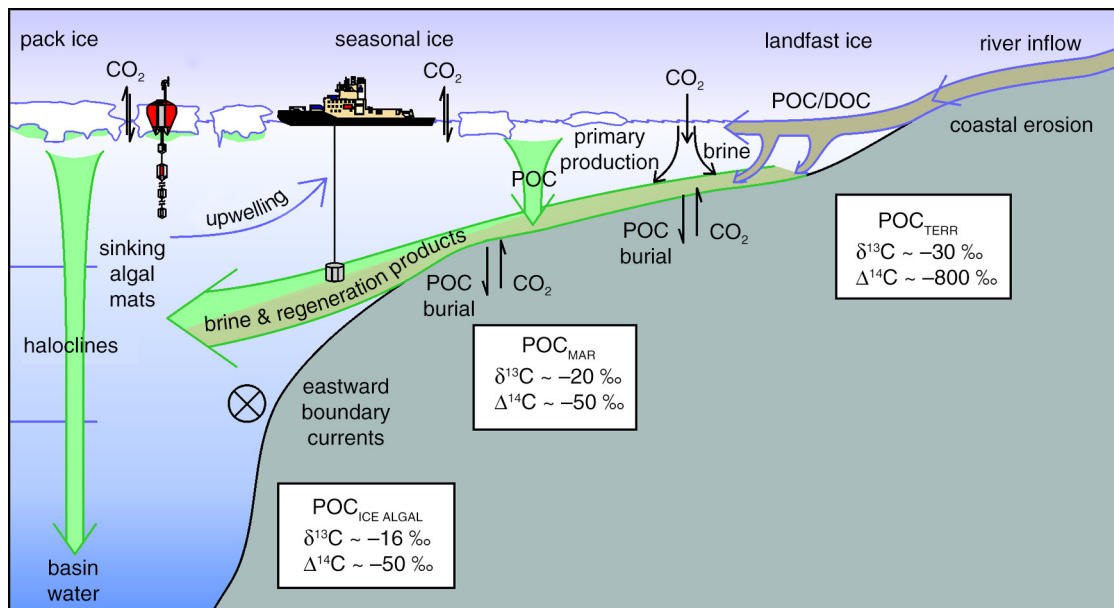
Fig. 3 Carbon transformation in shelf seas with substantial terrestrial organic carbon input. Composition estimates based on Goñi et al. (2005) and Stein & Macdonald (2004). Particulate organic carbon and dissolved organic carbon are abbreviated to POC and DOC, respectively.

regular field studies of the water column over decadal time periods to develop confident estimates of trends. This approach is needed given that these shelf seas are dynamic with, for example, river-plume distribution being highly affected by dominating wind fields in any particular season leading to variable extents of the CO_2 supersaturated regions (e.g., Pipko et al. 2010).

Ideally several transects from close to the river mouths out to the shelf slope should be sampled (Fig. 4). The Laptev Sea provides a suitable candidate for a transect along about 130°E where previous studies funded by various projects have built up a database spanning more than a decade. The western East Siberia Sea presents another area heavily impacted by terrestrial organic matter, and a section along about 155°E provides another suitable candidate. Water should be collected from the surface to the bottom and determined for, in addition to temperature and salinity, at least two of the carbon system parameters—dissolved inorganic carbon (DIC), total alkalinity (TA), pH and pCO_2—as well as DOC, POC, nutrients, oxygen and the isotopes ^{13}C and ^{18}O.

The seasonal variability of the river plume can, to some extent, be investigated by ship-based investigations, but a more fruitful and cost-efficient approach is likely by satellite observations. This will give a qualitative view of the general spreading of the river plume to which any ship-based study can be compared. Moorings close to the river mouth present a logistic challenge as the water is quite shallow and ridges of sea ice can build up when the wind pushes the ice towards land. However, moorings

are useful towards the shelf edge, but more for looking at near-bottom shelf export into the interior ocean utilizing sensors for backscatter (e.g., O'Brien et al. 2006), including any potential seasonal variability.
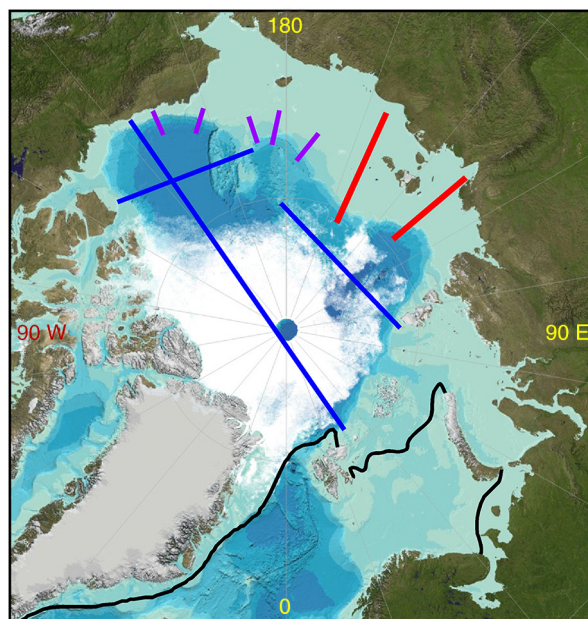

Fig. 4 Map with suggested transects for the study of the Arctic Ocean carbon system: red for following the land, burgundy for studying the boundary current contribution and blue for the central basins. Illustrated are the sea-ice conditions at the minimum in September 2012 (white shading) and with maximum in March 2012 demarcated by the black lines.

Investigation of the water column properties would benefit from complementary sediment studies, which could be conducted as focused investigations of sedimentary processes removing carbon through burial, or providing remineralized products from organic matter back to the water column through benthic respiration. For example, acoustic measurements could be used to determine the sediment structure and layer thickness along the section, and sediment cores—both long cores and shorter multiple cores with undisturbed surface sediments—could be applied to the determination of organic matter processes, discriminating between marine and terrigenous sources (e.g., Goñi et al. 2013). While such water column studies ought to be performed regularly, say, every third year, the sediment investigations can be done at longer intervals, although they do need to cover the same total timeframe of more than a decade.

Changes in the primary production

High primary production has always occurred over the shelf seas receiving nutrients imported from the south, like the Barents and Chukchi seas, with lower production occurring over the interior shelf seas—Kara, Laptev, East Siberian and Beaufort seas (Sakshaug 2004; Carmack et al. 2006). The limiting factor for production has mainly been the supply of nutrients, although light can play a role in timing and location. In the central Arctic Ocean, on the other hand, primary production has been low, especially new primary production (Anderson et al. 2003). Here, nutrient supply is restricted, but light conditions under multi-year pack ice have also limited productivity. Over the last few years, substantial production of microplankton (Arrigo et al. 2012), algae anchored in troughs and depressions under ice floes (Boetius et al. 2013) and generally higher primary production (Brown & Arrigo 2012) have been reported. These increases in organic production in the upper ocean are suggested to be a result of changes in the summer sea ice, which is thinner, covers less ocean area and contains more melt-ponds. Furthermore, the changes in sea-ice condition appear to have led to a substantive flux of particulate matter to the basins (Boetius et al. 2013). Model simulations suggest that primary production in an Arctic Ocean with less summer sea ice may change most in the seasonal ice zone (Wassmann et al. 2010). Furthermore, remote sensing of ocean colour has been used to infer that substantial increases in chlorophyll concentrations have occurred during the last decade (Arrigo et al. 2008). However, direct observations are limited and cannot directly be coupled to changing sea-ice conditions, whereas remote sensing data are not accurate enough over a sufficient long time to state a trend.

Observational approaches for primary production.

In a future with less sea ice during the productive seasons, there will be variable light conditions, making primary production spatially patchy. Furthermore, the balance between ice-algal production and pelagic production will likely change as light penetrates deeper in the ocean, and first-year sea ice that melts completely may produce brief episodes of vertical flux involving organic mats that, nevertheless, are important in terms of total annual production. These circumstances set special constraints on observations, emphasizing a need for high temporal or spatial coverage, or both. Spatial coverage of surface water can be achieved by continuous measurements during research cruises, while temporal coverage that includes ice cover and open water can only be made by autonomous measurements. The latter are likely best accomplished by buoys attached to sea-ice floes as this would allow for measurements of the upper waters with less risk of destroying the instruments by pressure ridges (Krishfield et al. 1993; Honjo et al. 1995). However, there is also a need for time series in open water areas, which likely are best achieved by deploying drifting buoys for shorter summer periods. In conjunction with samples collected or measurements made in the water column, complementary measurements of ocean properties should be made by remote sensing. Presently, such measurements could include parameters like temperature, ice cover and condition of melt, and ocean colour (chlorophyll, CDOM), all of which would help interpret data collected along sections or by buoys. The temporal frequency and spatial coverage of these investigations cannot be too high/large but will, in practice, be set by economic limitations.

Parameters to be determined depend on the platform, but for the autonomous instrumentation they should include temperature, salinity, chlorophyll, pCO_2, oxygen and other relevant fluorescence properties. With the development of technology, these parameters may be expanded to measure a greater suite of relevant properties. The same properties should be determined in the surface water during cruises, but could be complemented by other constituents like argon/oxygen ratio, nutrients, DIC or TA, ^{18}O, ^{13}C, DOC and filtration of the water to measure particulate inorganic carbon (PIC) and POC or establish the biological species composition. Furthermore, it would be useful to estimate primary productivity from incubation experiments. Complementary measurements at intervals of all the organic and inorganic constituents (particulate and dissolved) of the carbon system together with ^{13}C and ^{14}C for selected profiles would permit a more sophisticated understanding of

processes affecting terrestrial and marine components of the carbon system and their evolution over time (see, e.g., Griffith et al. 2012).

Traditionally, remote sensing has been applied to a wide variety of physical properties including currents, waves, sea level, ice distribution and so on, but the direct application to the carbon system has been more limited. Evaluation of chlorophyll from ocean colour measurements has been an important focus for remote sensing in the Arctic and elsewhere, and these sorts of data have been applied to determining trends in primary production (e.g., Petrenko et al. 2013). However, as these sensors only see the surface layer, different methods have been applied to achieve the depth integrated primary production. Typically, these methods have been developed in other areas than the Arctic Ocean and are therefore not designed for some of the specific conditions encountered in ice-covered seas, such as in the marginal ice zone. Furthermore, the algorithms for computing chlorophyll from the spectral signals include some uncertainties in regions of much suspended matter, as occurs in waters affected by the enormous rivers entering the Arctic shelf seas. Ocean colour may also be used to determine terrigenous CDOM under the right conditions (e.g., Salisbury et al. 2001), and imaginative use of remote sensing has assisted the interpretation of inorganic carbon fluxes in the Arctic Ocean (Else et al. 2008; Lauvset et al. 2013). Other applications will likely be developed during the coming years that could prove even more important for monitoring the Arctic Ocean's carbon system.

Increased sedimentation of organic matter to the deep sea

Change in primary production is an important factor by itself as are impacts on higher trophic levels. However, for changes in primary production to affect the net air–sea flux in the Arctic Ocean, alteration in the organic sedimentation out of the upper waters is required. Recycling of organic matter within the waters of the winter mixed layer will only have a seasonal impact and will not modify net inter-annual fluxes. Given that vertical fluxes within the interior Arctic Ocean are presently very low (Honjo et al. 2010; O'Brien et al. 2013), even a small change—especially into the older basin waters—could have a major effect on the Arctic Ocean's carbon budget.

A change in vertical flux can come about by a shift in the magnitude of primary production at the surface or, more likely, by shifts in the species composition of both primary and secondary producers. One example is the

sea-ice diatom *Melosira arctica* that recently was found freshly deposited in large quantities at the deep-sea floor (4000 m) of the central Arctic basins (Boetius et al. 2013). If this enhanced vertical flux is a result of sustained productivity, it will have a notable effect on the vertical carbon transport out of the mixed layer. However, the ultimate limiting factor of export production is nutrient supply, which will set the upper limit to flux out of the mixed layer. The exact magnitude of nutrient supply to interior ocean surface water is determined mainly by the influx of waters from the surrounding oceans, but also by the input from river runoff and to a lesser degree by mixing of nutrients from subsurface waters to the surface layer. The reason why the latter has a minor impact on the carbon transport to deeper layers is that at the same time as nutrients are supplied so will be the companion metabolic product: inorganic carbon. Only deviations in the P:N:C ratio of the supply relative to that of export production counts.

Observational approaches for sedimentation of organic matter. Observation of shifts in export production is difficult to accomplish over a short time scale because it is very patchy on both temporal and spatial scales. Hence, there is a need for a long-term approach with very accurate investigations aimed at capturing the integrated signal accumulated in intermediate and deep waters of the central basins. This would require traditional cruises where waters at different depths from the bottom to the surface are analysed for oxygen, nutrients and the carbon system parameters. It is well known that most of the organic matter from plankton that sediments through the water column is degraded at shallower depths and only a small fraction reaches the very deep layers. However, larger algae, like those that grow at the bottom of sea ice, sediment much faster when shed as algal mats, and can therefore easily reach the seafloor before degradation (Boetius et al. 2013). As shown below, it would be suitable to perform these traditional cruises with a frequency of about every five years.

To get a perspective on the magnitude of changes one can expect if the export production increases in the central Arctic Ocean, we can make a computation of the constraints. Assuming that an average of 2 Sv of seawater of a 1 μmol L^{-1} phosphate concentration enters the photic zone of the Arctic Ocean annually and that one quarter (productive season) of this is consumed within the shelf seas during the growing season, the supply to the deep central Arctic Ocean would be 47×10^9 mol yr^{-1}. Distributing this evenly throughout the deep ocean area, 4737×10^9 m^{-2}, implies a supply of about 0.01 mol m^{-2} yr^{-1}. If all this phosphate were to be consumed by primary production in the photic zone and all of the

resultant organic matter exported from the mixed layer to then decay over a 1000-m-thick water column beneath the mixed layer, the phosphate concentration would increase by ca. 0.01 µmol L^{-1} yr^{-1}. Using the classical RKR ratio (Redfield et al. 1963) of P:C:O_2 of 1:106:-135, the shift in both oxygen and DIC would be approximately 1 µmol L^{-1}. A change of that order would be possible to observe in a 5–10 year period, but for this to be relevant for the bottom waters fast-sinking organic matter, like sea-ice algae, would be required. Measurements of oxygen, nutrients and DIC should be complemented by a determination of the transient tracer field, for example, chlorofluorocarbons (CFCs) or sulphur hexafluoride (SF_6), in order to deduce potential changes in ventilation as well as the input of anthropogenic CO_2.

Furthermore, determination of POC and PIC at different depth levels can give indications of the export, although the patchy nature of sedimentation makes it essential to evaluate the data with care. The use of sediment traps could provide better seasonal coverage, but they need to be deployed over several years in order to yield robust statistics, over time, in any potential trend in sedimentation rate. Such traps would need to have the capacity to capture both the background vertical flux and episodic events from sinking algal mats. The ratio in POC to PIC is relevant for the plankton species composition and adds to the issue of ocean acidification. On a longer time scale it would, of course, also be relevant to collect sediment samples and to photograph the sea bottom.

Increased air–sea exchange in an ocean with less summer sea-ice coverage

In the summer surface waters of the ice-covered central Arctic Ocean, pCO_2 is largely undersaturated relative to the atmosphere (Bates & Mathis 2009; Jutterström & Anderson 2010). This undersaturation is sustained by primary production and cooling of the inflowing waters in the Bering/Chukchi and Barents seas, together with an exchange between ocean and atmosphere that is restricted by the ice cover. With loss of the permanent pack ice, which leads to less sea-ice coverage in summer and more open leads and cracks in the ice in winter, gas exchange will likely be amplified.

Seasonal variability of pCO_2 has been determined at the southern margin of the central Arctic Ocean, for example, during the International Polar Year Circumpolar Flaw Lead System Study (Barber et al. 2010). As the surface waters in that region were heavily impacted by the interaction with the bottom and the surrounding shelf seas (Else et al. 2011), one cannot interpolate these data to the central Arctic Ocean.

Observational approaches for air–sea exchange.

With the new sea-ice state of the Arctic Ocean, there have been several scientific cruises to the interior regions during summer by ships from various nations. An immensely improved view of pCO_2 distribution would result if these ships were to be equipped with continuous measurement systems for pCO_2 in surface water using a seawater loop installed in the hull. Ideally, this type of measurement should be conducted widely over the entire ocean but, practically, the best that could be achieved for the Arctic would be to instrument all research vessels. However, there is also an urgent need to get a better knowledge of the seasonal development of pCO_2 in the upper central Arctic Ocean. There are sensors available for long-term observations of pCO_2, and it would be feasible to mount these in ice-tethered moorings at a depth of 5–10 m below the bottom of the ice. An alternative, and also complementary, approach would be to extend the network of stations measuring air pCO_2 around the Arctic, and combine these with a good atmospheric transport model. Such a data set might allow for a definitive determination of changes in air CO_2 resulting from air–sea exchange, especially if such measurements were complemented by oxygen measurements to help deconvolute any changes in the contribution from the terrestrial biosphere.

Sea-ice-produced brine increases carbon sequestration by ventilation

It is well known that the upper halocline of the Canadian Basin is enriched in nutrients as a result of shelf processes in the Chukchi–East Siberian Seas region (e.g., Jones & Anderson 1986). The cause of this signature includes a chain of processes where the produced organic matter sinks to the shallow bottom of this extensive region towards the end of the productive season (Fig. 2). This time period coincides with the start of sea-ice formation, which results in the expulsion of brine and formation of a thin, high-salinity bottom layer. The organic matter decays, and the resulting chemical constituents, for example, nutrients and CO_2, accumulate in the bottom water. Over time, the nutrient- and CO_2-rich, highly saline bottom water flows north towards the shelf slope where it interleaves with interior water at a level that matches its density (Figs. 2, 3).

The flux of CO_2 between the atmosphere and the sea is largely determined by the exchange across the surface water film. It has been suggested that this exchange is very efficient during sea-ice production (Anderson et al. 2004; Miller et al. 2011; Else et al. 2012), leading to promoted net air–sea flux as long as there is a differential

in pCO_2 across the interface. Consequently, increased sea-ice production following a larger open water area in the summer could lead to more brine production and therefore an amplified uptake of CO_2 from the atmosphere. In the shallow shelf seas, the CO_2 concentration would build up in the high-salinity bottom waters that flow off into the deep basin. If the sea-ice production also starts farther away from the coast, where there is less influence from freshwater runoff, it could lead to a higher salinity of the bottom water and therefore also a potential to penetrate deeper into the water column of the deep basins. There are indications that this has occurred during the last decade in the region north of the New Siberian Islands (Anderson et al. 2013).

Observational approaches for carbon sequestration. The production of brine-enriched water occurs at various places around the Arctic Ocean, especially in regions of polynyas. However, if the waters are too deep, or freshwater inputs too large, the brine is mixed with surrounding waters before it reaches the bottom and no high-salinity bottom water is formed. Also, for atmospheric CO_2 to be sequestered, the waters must be undersaturated with respect to CO_2 when the sea ice is produced. The conditions of high productivity sustained by nutrients from inflowing waters, brine production and shallow water depths (≤ 50 m) are met over the shelf region spanning the area from the New Siberian Islands to the Alaskan coast (Fig. 2). Observations should be focused in this area. Preferably several sections covering the region from the outer shelf and across the slope into the deep basin should be investigated (Fig. 4). The approach would be to take sequences of stations where water is collected at several depths with emphasis on the salinity range of about 32.5 and higher down to the bottom (e.g., see figure 7 in Weingartner et al. 1998).

As the dominating flow pattern along the shelf slope is from west to the east, sections at several longitudinal locations would provide information on both potential formation regions as well as temporal variability. These studies should include the determination of at least two of the carbon system parameters (DIC, TA, pH and pCO_2), nutrients, oxygen and the isotopes ^{13}C and ^{18}O, and preferably also transient tracers to get a view of the ventilation rate of the deeper waters. There is annual variability in the sea-ice coverage of the shelf seas, and there is therefore likely also variability in the chemical signals of the waters leaving the shelves. For trends to be detected, such studies need to be repeated regularly over a time period of at least a decade.

Summary and conclusions

The Arctic Ocean's carbon cycle is uniquely sensitive to warming because of the extensive influence of ice on land and over the sea. In the adjacent drainage basins, permafrost contains large quantities of terrigenous carbon. With thawing, this carbon may be released as ancient POC due to riverbank and coastal erosion, and younger DOC produced by changing vegetation and a more active surface layer in the soil. After reaching the ocean, metabolism of this carbon in shelf-bottom waters can then lead to greater contributions of DIC to interior ocean basins through thermohaline processes. Over the sea, the large-scale shift of permanent pack ice to seasonal ice will affect ocean processes such as atmosphere–ocean exchange, primary production, vertical flux of organic matter and the production of brine over shelves. These processes together then have the potential to affect the net exchange of CO_2 with the atmosphere to a degree that influences climate. To address the question of how warming will affect the Arctic's land and ocean regions to a level at which realistic scenarios of the future can be proposed, there is a need for joint coordinated international observations.

Much can be gained by planning combinations of observations that fit well together, both when it comes to the observational areas but also in the application of common sampling methods. Today several nations have research vessels that can operate throughout most of the Arctic Ocean during summer, making the potential for such international coordination great.

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