ARTICLE IN PRESS

Deep-Sea Research II ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Regular article

Variations in the proportions of melted sea ice and runoff in surface waters of the Chukchi Sea: A retrospective analysis, 1990–2012, and analysis of the implications of melted sea ice in an under-ice bloom

Lee W. Cooper [a,*], Karen E. Frey [b], Christie Logvinova [b], Dana M. Biasatti [a], Jacqueline M. Grebmeier [a]

[a] University of Maryland Center for Environmental Sciences, Solomons, USA
[b] Clark University, Worcester, USA

ARTICLE INFO

Keywords:
Chukchi Sea
Stable oxygen isotopes
Sea ice melt
Under-ice bloom
Marginal ice zone

ABSTRACT

Retrospective analysis of apparent freshwater isotopic end-members through use of salinity–δ^{18}O mixing lines for 15 research cruises from 1990 to 2012 indicates that the freshwater contributed by melted seasonal sea ice does not directly reflect the large change in seasonal sea ice extent in the Chukchi Sea observed over the past several decades. Instead the freshwater that appears to be contributed by melting sea ice relative to runoff is highly dependent upon cruise track (e.g. proximity to runoff) and sampling capabilities in sea ice (icebreakers sample waters with less melted sea ice). Although under certain circumstances, including later seasonal sampling and recurrent cruise tracks between years, increased melted sea ice in surface waters can be readily detected. This suggests a more ephemeral influence of melted sea ice on ecosystem properties despite the significant decadal changes in sea ice extent. As a recent case study, the freshwater component present in waters within an under-ice bloom in the Chukchi Sea reported by Arrigo et al. (2012), included a significant fraction (~10% or more) of freshwater, primarily from melted sea ice. These results suggest that this under-ice bloom, which extended more than 60 km under solid ice still might be reasonably interpreted as being part of a continuum with other ice melt-associated blooms and not independent of sea ice retreat and dissolution.

1. Introduction

The accelerated retreat of seasonal sea ice from the continental shelf of the Chukchi Sea has been one of the key geographic regions driving the overall decline in the extent of Arctic Ocean sea ice (Frey et al., 2014). While seasonal sea ice decline over the past three decades has been well documented from satellite sensors, the specific impacts of sea ice decline on the upper water column and other ecosystem components is more challenging to observe. For example, the freshwater content of melted sea ice lowers alkalinity and buffering capacity relative to runoff (Yamamoto-Kawai et al., 2009; Chierici and Fransson, 2009; Fransson et al., 2013; Robbins et al., 2013). Recent shifts to smaller cell sizes in oligotrophic Canada Basin phytoplankton are thought to be the result of increases in melted sea ice in surface waters (Li et al., 2009), although these biological changes are likely to be harder to detect on the more productive continental shelf. The freshwater component of melted sea ice also carries low concentrations of dissolved organic carbon (DOC) and the related component, chromophoric dissolved organic material (CDOM) that strongly absorbs photosynthetically active radiation. Although DOC is generated during production in sea ice algal communities (Riedel et al., 2008), it is much less refractory than DOC contributed by runoff, so higher, persistent DOC concentrations in the water column are typically consistent with runoff rather than melted sea ice (e.g. Kattner et al., 1999; Dittmar and Kattner, 2003; Cooper et al., 2005).

As a result, mixing of melted sea ice with freshwater from runoff will likely increase light transmission, potentially increasing biological production if sufficient nutrients are available, as well as changing bacterial cycling of DOC. A shift to more biological production on Arctic shelves has been hypothesized to result from sea

* Correspondence to: Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, PO Box 38, Solomons, MD 20688, USA.
Tel.: +1 410 326 7359.
E-mail addresses: cooper@umces.edu (L.W. Cooper), kfrey@clarku.edu (K.E. Frey), Dana.Biasatti.1@nd.edu (D.M. Biasatti), jgrebmei@umces.edu (J.M. Grebmeier).

http://dx.doi.org/10.1016/j.dsr2.2016.04.014
0967-0645/

Please cite this article as: Cooper, L.W., et al., Variations in the proportions of melted sea ice and runoff in surface waters of the Chukchi Sea: A.... Deep-Sea Res. II (2016), http://dx.doi.org/10.1016/j.dsr2.2016.04.014

ice retreat, and observations of high primary productivity and high concentrations of chlorophyll in blooms located under thinning Arctic sea ice (Mundy et al., 2009; Arrigo et al., 2012, 2014; Mundy et al., 2014) have stimulated interest in the importance of such blooms in the overall productivity of the Arctic. Light transmission through melt ponds with low CDOM absorbance versus bare ice help explain the availability of sufficient light to sustain photosynthesis (Frey et al., 2011). Since these blooms, and an often-present subsurface chlorophyll maximum, cannot be observed accurately from satellite platforms, it is clear that in-situ measurements are required to better quantify the overall magnitude of Arctic productivity under a changing sea ice regime.

Despite these potentially important ecosystem effects, the residence time of surface waters on Arctic Ocean shelves is short, 1–3 years (Schlosser et al., 1994), and likely shorter on inflow shelves such as the Chukchi (Weingartner et al., 2005). As a result, the broader ecosystem impacts of earlier and more extensive melting of seasonal sea ice on the continental shelf of the Chukchi Sea, where seasonal sea ice retreat has been extensive (Frey et al., 2014), remain elusive to identify and may be ephemeral in duration.

One key tracer for melted sea ice in surface seawaters is the ratio of the two most common isotopes of oxygen, ^{18}O and ^{16}O. Because of stepwise isotopic fractionation during evaporation of water, which favors the lighter isotopes of oxygen, meteoric precipitation is depleted in the heavier isotopes of oxygen upon return to the earth surface, and the effect is greater at higher latitudes and elevations (Dansgaard, 1964). As a result of brine rejection during sea ice formation, sea ice approaches freshwater in salinity (~4 psu; Melnikov et al., 2002), but isotopically, melted sea ice is more similar to the surface seawater from which it forms ($\delta^{18}O = \sim -1‰$) than high latitude runoff and precipitation ($\delta^{18}O = \sim -20‰$). This distinct and highly significant difference (analytical precision for $\delta^{18}O = \pm 0.10$ or better) has facilitated the widespread use of $\delta^{18}O$ values as a means to quantify the contributions of melted sea ice versus meteoric runoff to surface sea water at high latitudes (e.g. Bauch et al., 1995 and Ekwurzel et al., 2001).

The stable oxygen isotope composition of the Chukchi Sea and upstream Pacific-influenced waters flowing north from Bering Strait has been well studied over the past two decades, (e.g. Grebmeier et al., 1990; Cooper et al., 1997', 1999', 2005, 2006; Clement et al., 2004), over the same time frame that seasonal sea ice extent and duration has significantly changed. We chose in this study to re-visit these published data in conjunction with more recently collected, and not previously published data to evaluate whether the changes in the sea ice regime of the Chukchi Sea that have been observed over the past two decades are reflected in simple indices of melt water contributions such as the apparent end-member isotopic composition of freshwater in plots of salinity versus $\delta^{18}O$ values, expressed by the relation

$$\delta^{18}O_{V-SMOW} = (R_{sample} - R_{standard} / R_{standard})^{*}1000‰,$$

where $R = {}^{18}O/{}^{16}O$ and V-SMOW is Vienna Standard Mean Ocean Water, as distributed by the International Atomic Energy Agency. Thus, in a regression of salinity (x-axis) versus $\delta^{18}O_{V\text{-}SMOW}$ (y-axis), the y-intercept at 0 salinity corresponds approximately to the freshwater source, with pure runoff$\sim = -20‰$, and increasing additions of melted sea ice resulting in less negative apparent end-members. This end-member evaluation is an approximation because continental shelf waters in the Chukchi Sea above the upper halocline (salinity=33.1) have undergone overwinter brine injection during sea ice formation, so apparent mixing lines of $\delta^{18}O$ and salinity between water with a salinity of 33.1 and runoff are typically displaced towards higher salinity, with the brine injection impact slightly higher as the upper halocline 33.1 salinity is approached (Cooper et al., 2005). Our retrospective analysis of previously published stable isotope data involved evaluating whether apparent freshwater end-members have increased since 1990 as sea ice has melted earlier seasonally and retreated to a greater extent over the Chukchi continental shelf.

A simplified approach is to estimate the fractions of melted sea ice versus runoff within seawater parcels; for simplicity, core Atlantic water is used as the most saline and isotopically heaviest end-member fraction in a three-component mixing model

$$f_{sim} + f_{runoff} + f_{Atlantic} = 1$$
$$f_{sim} * \delta^{18}O_{sim} + f_{runoff} * \delta^{18}O_{runoff} + f_{Atlantic} * \delta^{18}O_{Atlantic} = \delta^{18}O_{observed}$$
$$f_{sim} * \text{salinity} + f_{runoff} * \text{salinity} + f_{Atlantic} * \text{salinity} = \text{salinity}_{observed}$$

where f=fraction of the component, sim=sea ice melt, runoff=freshwater from meteoric water, including the meteoric water that is contributed through the Bering Strait inflow. In this analysis, core Atlantic layer water in the Arctic Ocean, with a salinity of 34.8 and a $\delta^{18}O$ value of $+0.3‰$ (Ekwurzel et al., 2001) mixes with less saline waters that include both meteoric water and melted sea ice, as well as Pacific waters flowing through Bering Strait. We account for the contribution of the Bering Sea inflow by using the apparent oxygen isotope composition of freshwater (i.e. salinity=0; $\delta^{18}O$ of $-21.35‰$) flowing through the Strait; this stable isotope end-member corresponds to the most up-to-date regressions of $\delta^{18}O$ values versus salinity for waters collected solely within Bering Strait (Cooper et al., 2006 and unpublished data). We assume that the oxygen isotope composition of freshwater flowing through Bering Strait is the predominant source of meteoric water because the Chukchi shelf waters sampled were directly influenced by the Bering Strait inflow from the Bering Sea (Weingartner et al., 2005). Nevertheless, the isotopic composition of runoff directly into the Chukchi Sea, whether from rivers or melted snow on sea ice, is not likely to be greatly different from runoff carried within the Bering Strait inflow (Cooper et al., 2008). Finally, based upon our own measurements of sea ice during the ICESCAPE cruises, the salinity of sea ice was set to 4, with a $\delta^{18}O$ value of $-1‰$ (Logvinova et al., this issue).

This approach does not require separating Atlantic and Pacific waters, which vary seasonally in salinity, and does not require considering possible decadal changes in the freshwater flux through Bering Strait (Woodgate et al., 2012). We used this approach to estimate melted sea ice contributions in Chukchi Sea waters sampled during the July 2011 NASA-supported ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment) program in the Chukchi Sea, where evidence of high productivity was attributed to thinner sea ice and transmission of light through melt ponds.

2. Methods

Stable oxygen isotope and salinity data were re-evaluated from 16 research cruises that sampled in the Chukchi Sea between 1990 and 2012 (Table 1). Regression lines of the form $y = m^{*}\delta^{18}O + b$ were calculated for each individual cruise and the differences among apparent freshwater end-members (b) were considered in the context of such factors as the timing of the cruise (e.g. later in the ice melt season can be expected to have less negative $\delta^{18}O$ end-member values). Other complicating factors such as the geographical extent of sampling and whether ship platforms used would sample more effectively in sea ice (i.e. icebreakers) versus ships limited to open water were also considered. In the end, after considering those potential biases, the goal was to evaluate whether the freshwater contributions of melted sea ice in Chukchi Shelf surface waters could be unambiguously observed to increase as sea ice has declined over the past two decades.

Please cite this article as: Cooper, L.W., et al., Variations in the proportions of melted sea ice and runoff in surface waters of the Chukchi Sea: A.... Deep-Sea Res. II (2016), http://dx.doi.org/10.1016/j.dsr2.2016.04.014

New stable isotope data are also presented here from one of the ICESCAPE cruises, which sampled an under-ice phytoplankton bloom on 4–8 July 2011 in the Chukchi Sea. In particular, stations 57–65 during this cruise were sampled under complete ice cover, and high levels of chlorophyll were observed in the upper water column. More details, including the other parameters measured during the cruise are available in Arrigo et al. (2012) and Arrigo et al. (2014) and associated Supplementary information. Data are available from http://datadryad.org/resource/doi:10.5061/dryad.4dn793t6 and will be ultimately archived at http://oceandata.sci.gsfc.nasa.gov/. During this cruise, we obtained water samples from the CTD rosette, which were returned to the Chesapeake Biological Laboratory of the University of Maryland Center for Environmental Science in sealed vials with precautions undertaken to prevent evaporation (and isotopic fractionation). Water samples were analyzed by equilibration with carbon dioxide using a Thermo Finnigan Gas Bench II peripheral linked to a continuous flow Delta V Plus isotope ratio mass spectrometer. Analytical precision was better than ±0.1‰ and was assessed by analysis of in-house water standards during sample analysis and calibration to international water isotope standards (V-SMOW, SLAP, GISP). Data were normalized as per recommendations of Paul et al. (2007).

3. Results

Evaluation of the salinity–δ^{18}O mixing lines for the 16 different cruises shows a wide variety of apparent freshwater end-members (Table 1). Sampling locations associated with these cruises are available on Fig. 1. The three separate Russia-US Long-term Census of the Arctic (RUSALCA) cruises in 2004, 2009 and in 2012 that occupied many of the same stations on the Chukchi shelf showed a

Table 1
Chukchi Sea cruise data used in this study. Data are from Cooper et al. (1997, 1999, 2005, 2006, and unpublished data).

Cruise	Dates	Equation	*N*=	Comments
Surveyor	September 1990	$Y=-17.22+0.502$	157	Sampling in Kotzebue Sound provided river signal
Alpha Helix 165	August–September 1992	$Y=-6.88+0.179$	74	Some work near ice edge
Alpha Helix 166	September–October 1992	$Y=-17.11+0.517$	145	East Siberian Coastal Current
USCGC Polar Star	August 1993	$Y=-12.81+0.339$	238	Open water to heavy ice
Alpha Helix 174	September 1993	$Y=-11.69+0.332$	107	Dual distribution of end-members
BERPAC 1993	September 1993	$Y=-7.56+0.199$	30	Work near ice edge in late summer
Alpha Helix 189	September 1995	$Y=-13.74+0.356$	146	Includes work in East Siberian Sea (river signal)
USCGC Healy 02-01	May–June 2002	$Y=-26.43+0.760$	254	River signal, little ice melt
USCGC Healy 02-03	July–August 2002	$Y=-10.6+0.281$	125	Strong dual end-member separation
USCGC Healy 04-02	May–June 2004	$Y=-19.19+0.541$	70	Early season sample prior to sea ice melt
USCGC Healy 04-03	July–August 2004	$Y=-16.85+0.482$	106	Mid-summer sampling
Rusalca 2004	August–September 2004	$Y=-22.59+0.663$	63	Late summer sampling
Rusalca 2009	August–September 2009	$Y=-13.11+0.3623$	79	Late summer sampling
USCGC Healy 10-01	July–August 2010	$Y=-13.14+0.3615$	409	Mid-summer sampling
USCGC Healy 11-01	July–August 2011	$Y=-12.03+331$	634	Under-ice bloom
Rusalca 2012	August–September 2012	$Y=-8.45+0.823$	90	Sea ice minimum

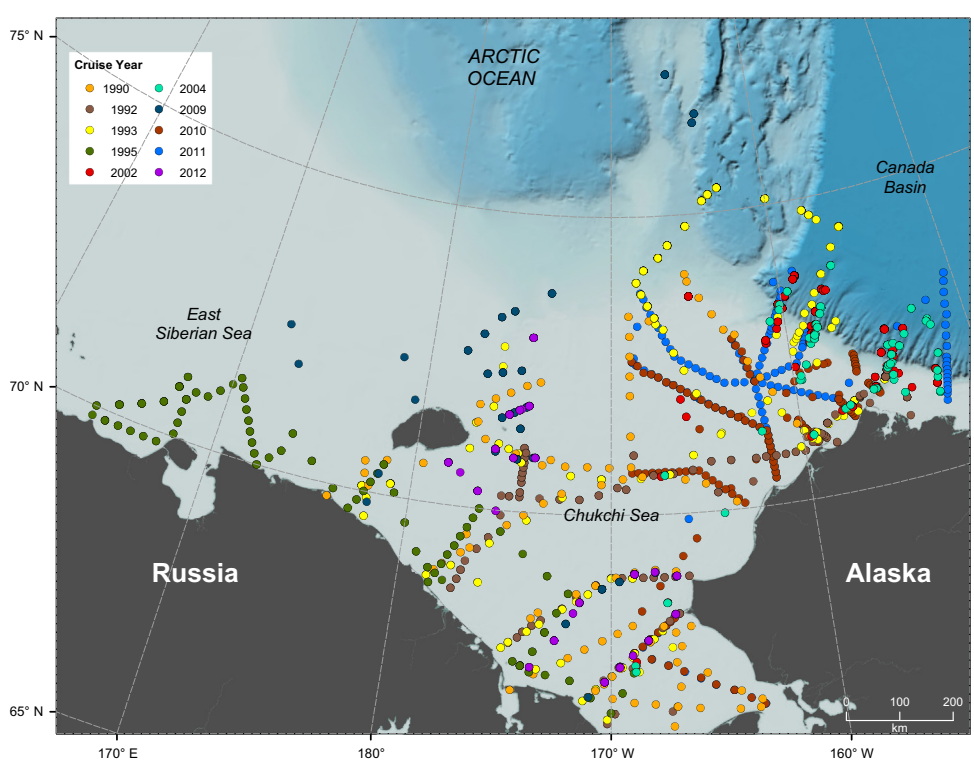

Fig. 1. Location of ship tracks in the Chukchi Sea, 1990–2012 for collections of water samples for δ^{18}O values from 16 research cruises that were the subject of retrospective data analysis. The location of the two additional ICESCAPE cruises in 2010 and 2011 (δ^{18}O data not previously reported) are also plotted here.

large relative decadal shift to surface meltwater by 2012 as summer sea ice extent reached a minimum. By comparison in 2004, the freshwater component consisted almost entirely of runoff; 2009 was intermediate between 2004 and 2012 when melted sea ice dominated (Fig. 2). However, examination of the other cruise freshwater end-members show that there are clearly other complexities and sampling biases that can play a role in determining the apparent freshwater contributions from melted sea ice relative to runoff. For example, Alpha Helix cruises 166 and 189 were specifically planned to sample waters influenced by the Siberian Coastal Current (Weingartner et al., 1999; Münchow et al., 1999; Khim et al., 2003), so it is not surprising that during Alpha Helix cruise 166 and 189, waters sampled had relatively high degrees of runoff (end-member δ^{18}O value = −17.11‰ and −13.74‰, respectively) derived in large part from the Kolyma and other Siberian rivers that provide runoff that flows eastward in the Siberian Coastal Current through Long Strait into the Chukchi Sea. Sampling from icebreaker platforms (e.g. Healy cruises) also includes sampling in waters that have higher ice cover than sampled from less ice-capable vessels (e.g. Alpha Helix), so early season Healy cruises (e.g. Healy 02-01, Healy 04-02, Healy 10-01, Healy 11-01) tend to have freshwater end-members that reflect surface waters prior to substantial ice melt (freshwater end-member δ^{18}O < −10‰). Later season cruises in August-October, particularly on less ice-capable vessels have freshwater end-members with δ^{18}O > −10‰ (i.e. a melted sea ice signal) with the exception of the Surveyor cruise in 1990, which sampled in waters of Kotzebue Sound where there is a strong runoff signal from local rivers such as the Noatak and Kobuk (Cooper et al., 1997).

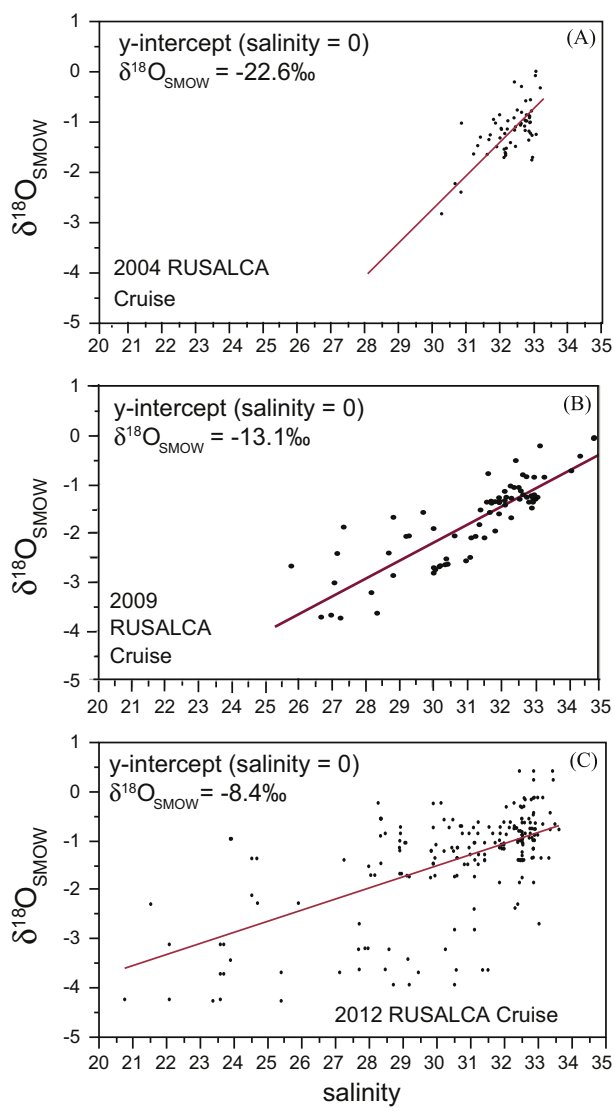

Fig. 2. δ^{18}O versus salinity plots for RUSALCA 2004 (a), 2009 (b) and 2012 (c) cruises showing an increasing contribution of melted sea ice to Chukchi shelf waters sampled during the three sampling periods in late summer in each of the three cruises.

The Healy 11-01 cruise is reported on in more detail here, as the data are not previously published, and observations of high productivity under the ice are pertinent to the influence of melted sea ice on upper ocean biogeochemistry. Sampling locations are shown on Fig. 3 and ^{18}O$_{V\text{-}SMOW}$ values for water samples collected on Healy 11-01 ranged from >0‰ (Atlantic water layers, where salinities >34) to −4.2‰ in low salinity surface waters. Samples were primarily collected on the shelf (<100 m), to 150 m in an area of high under-ice productivity, and to depths of 2100 m in a few deep profiles. When all δ^{18}O$_{V\text{-}SMOW}$ data are plotted against salinity for the entire cruise (Fig. 4 upper panel), the least squares fit line reaches the *y*-intercept of zero salinity at a δ^{18}O$_{V\text{-}SMOW}$ value of −12‰, indicating that the mean δ^{18}O value of freshwater present during the 2011 cruise was approximately half-way between expected meteoric water values (~−20‰) and melted sea ice (~−1‰), based upon the mean oxygen isotope compositions content of all sea ice collected during the 2010 and 2011 ICESCAPE cruises (Logvinova et al., this issue). Solving the three simultaneous equations for each end-member (Atlantic water, sea ice melt and runoff) shows a widespread sea ice melt component throughout surface and subsurface waters that were sampled, including within the under-ice bloom (Fig. 5). Note that negative sea ice melt fractions correspond to brine injection as a result of sea ice formation, so the positive fractions of melted sea ice are likely underestimates of actual melt water fractions because most Chukchi Sea waters have been influenced by brine injection (Cooper et al., 2005).

The samples collected at stations 57–65 (locations shown in Fig. 3; data plotted in Fig. 5 lower panel) [in the core of the under-ice phytoplankton bloom reported by Arrigo et al. (2012) and Arrigo et al. (2014)] show that for these stations, the *y*-intercept at zero salinity had a δ^{18}O value of −5.7‰, which indicates that much higher fractions of melted sea ice were present in surface waters. The contributions of the melted sea ice component overlapped with high chlorophyll biomass. These observations confirm that the under-ice phytoplankton bloom observed by Arrigo et al. (2012) and Arrigo et al. (2014) occurred in sub-surface waters with high proportions of melted sea ice.

4. Discussion

The range of freshwater end-members observed on the 16 different cruises tabulated between 1990 and 2012 (Table 1) indicate that cruise track, proximity to river outflows and other biases such as icebreaker platforms being able to sample in heavier ice where less melt has occurred are responsible for some of the variation in the freshwater isotopic end-member. In general, this makes use of the *y*-intercept for regressions of the type δ^{18}O = m^*salinity + b problematic for assessing changes over time in overall melted sea ice presence in surface Arctic Ocean waters. An example of an exception is the comparison among the three RUSALCA cruises in 2004, 2009 and 2012 (Fig. 2) that undertook very similar cruise tracks at the same time of year in the Russian Chukchi Sea (Fig. 1). Each successive cruise had increasing contributions of melted sea ice in September over time, with a maximum reached in 2012 at the time of the minimum sea ice extent in the satellite remote sensed record. This comparison shows a clear shift to freshwater

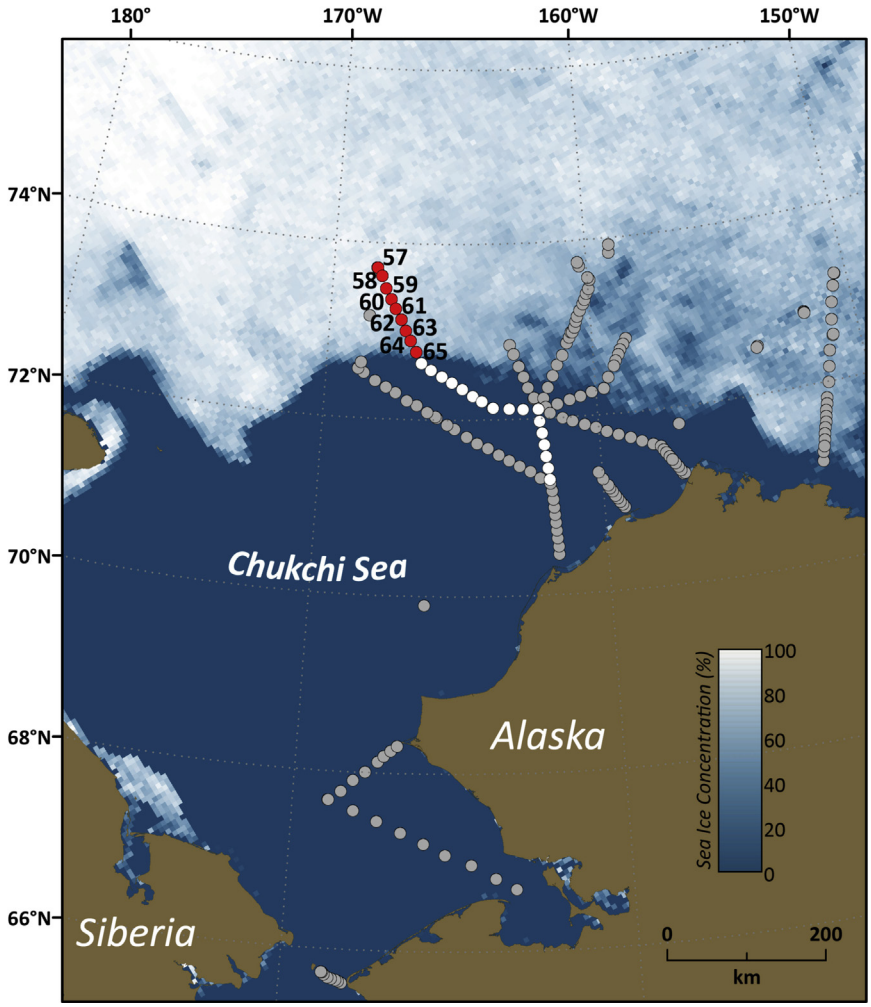

Fig. 3. Location of stations in under ice bloom, 4–8 July 2011. Under ice sampling stations are shown as red circles and are numbered. White circles are other stations in transect that are also shown on Ocean Data View plot (Fig. 5). Gray circles are all other stations occupied during cruise. Sea ice location is based up on AMSR-E sea ice concentration imagery, 8 July 2011.

components dominated by melted sea ice (Fig. 2). Despite this, larger scale, synoptic studies of the Arctic Ocean (e.g. Morison et al., 2012) indicate that freshwater produced from retreating seasonal sea ice cover plays a relatively insignificant role in freshwater storage in large reservoirs such as the Beaufort Gyre, which are controlled by changes in Arctic Ocean surface water circulation that bring runoff from Siberian sources into the North American basins instead of more direct export through the Trans-Polar Drift to the North Atlantic. Another example is the freshwater δ^{18}O *y*-intercept associated with Bering Sea waters flowing through Bering Strait (mean = −21.35‰; Cooper et al., 2006). The largely runoff signal associated with this stable oxygen isotope value indicates that over the course of annual cycles only insignificant contributions of melted sea ice relative to runoff are present in the flow passing north into the Chukchi Sea through the Bering Strait.

The overall conclusion is that analysis of apparent freshwater end-members makes the most sense in the context of individual cruises, and that the influence of melted sea ice is much more ephemeral over longer timescales such as annual seasonal cycles. On the other hand, apparent freshwater end-members for many of these cruises make sense in the context of the individual cruise, for example Alpha Helix cruises 166 (1992) and 189 (1995) that investigated processes in the Siberian Coastal Current, which is driven by a significant runoff component (Weingartner et al., 1999) that is confirmed by the runoff-like *y*-intercept δ^{18}O values where salinity reaches zero (Table 1).

As part of our efforts following the ICESCAPE cruise in 2011, we used this more contextual approach to determine the stable oxygen isotope compositions of sea ice and water samples in order to assess whether there was melted sea ice present in the waters supporting the under-ice phytoplankton bloom. For under-ice blooms, the possibility of assessing melted sea ice contributions to under-ice surface water has implications for understanding the evolution and development of these features. The vast majority of sea ice algal biomass in the Bering and Chukchi Sea adheres to the bottom 2 cm of sea ice (Melnikov et al., 2002; Cooper et al., 2013), which is in contact with high nutrient waters present early in the seasonal cycle (Codispoti et al., 2005). As a consequence, once dissolution of continuous sea ice cover has commenced, contributions of sea ice algae to ocean surface waters are inevitable, and it could be reasonably concluded that the presence of any under-ice productivity was related to at least some degree to sea ice algae melting out into the upper water column. It is also reasonable to assume that any water column with significant melted sea ice contains algal cells discharged into the upper water column from ice. The taxonomic distribution of phytoplankton sampled in this under-ice bloom are reported in detail by Laney and Sosik (2014), as well as by Balch et al. (2014). While some genera present in this bloom are typically thought of as pelagic (e.g. *Chaetoceros*), others are cryophilic (e.g. *Fragilariopsis*) or much more exclusively associated with sea ice (e.g. *Pseudonitzschia*). The same detailed phytoplankton community analysis that was documented in the

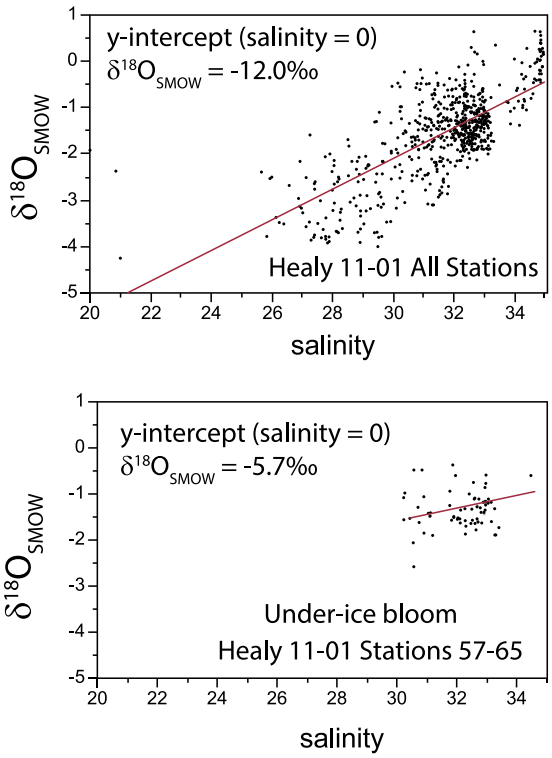

Fig. 4. δ^{18}O values plotted against salinity for all rosette water samples collected during the ICESCAPE cruise, Healy 11-01 in the Chukchi Sea (top panel) and the subset collected at stations 57–65 during observations of the under-ice phytoplankton bloom, 4–8 July 2011 (locations shown in Fig. 3). The *y*-intercept of the best-fit regression line can be used to approximate the δ^{18}O value of the freshwater (salinity=0) end-member (see text for further information). For the top panel, $\delta^{18}O = -12.03 + 0.331$*salinity; $r^2 = 0.51$, $n = 634$. Standard error associated with the $\delta^{18}O = -12.03$ (zero salinity) *y*-intercept is ± 0.40. For the bottom panel, $\delta^{18}O = -5.71 + 0.137$*salinity; $r^2 = 0.07$, $n = 44$. Standard error associated with the $\delta^{18}O = -5.71$ (zero salinity) *y*-intercept is ± 2.45.

water column has not been reported for the sea ice that was over this bloom. It is not certain that there should even be a direct relationship in species composition between sea ice algal communities and underlying water column communities to which they contribute in part (Rolf Gradinger, personal communication). Pelagic genera such as *Chaetoceros* have been observed trapped in new ice in the Beaufort Sea (Różańska et al., 2008) and factors such as sinking rates of aggregates (e.g. Fernández-Méndez et al., 2014) or pennate diatoms, and growth dynamics might make these communities unexpectedly different from one another even if the sea ice algal community is ultimately the source of cells for initiating production in the underlying water column.

A key question therefore is whether blooms that occur under Arctic sea ice are distinct productivity features unrelated to either sea ice algal productivity or subsequent marginal ice zone (MIZ) blooms that occur during the dissolution of high latitude seasonal sea ice. Both Arrigo et al. (2014) and Mundy et al. (2014) distinguished MIZ blooms from phytoplankton blooms that develop entirely beneath the sea ice and hypothesized that wider distributions of these under-ice blooms would require re-evaluation of overall biological productivity in the Arctic. Lowry et al. (2014) further developed this idea by estimating the occurrence of under-ice blooms based upon the absence of MIZ blooms following ice retreat, assuming that the lack of a MIZ bloom was a result of a prior unobserved under-ice bloom having removed all nutrients from the surface water column.

However, the presence of melted sea ice in an under-ice phytoplankton bloom, which was also recognized by Mundy et al. (2014), suggests that it is uncertain whether these blooms should be distinguished from ones resulting from the dissolution of melting sea ice. Instead these blooms might reasonably be considered to be part of a continuum that extends temporally as ice thins enough to both release algal cells from the underside of ice as well as to allow enough light transmission to sustain open water photosynthesis until nutrients are exhausted, often in a MIZ bloom with similar chlorophyll biomass as reported in the ICESCAPE under-ice bloom. Under conditions where ice is in slow

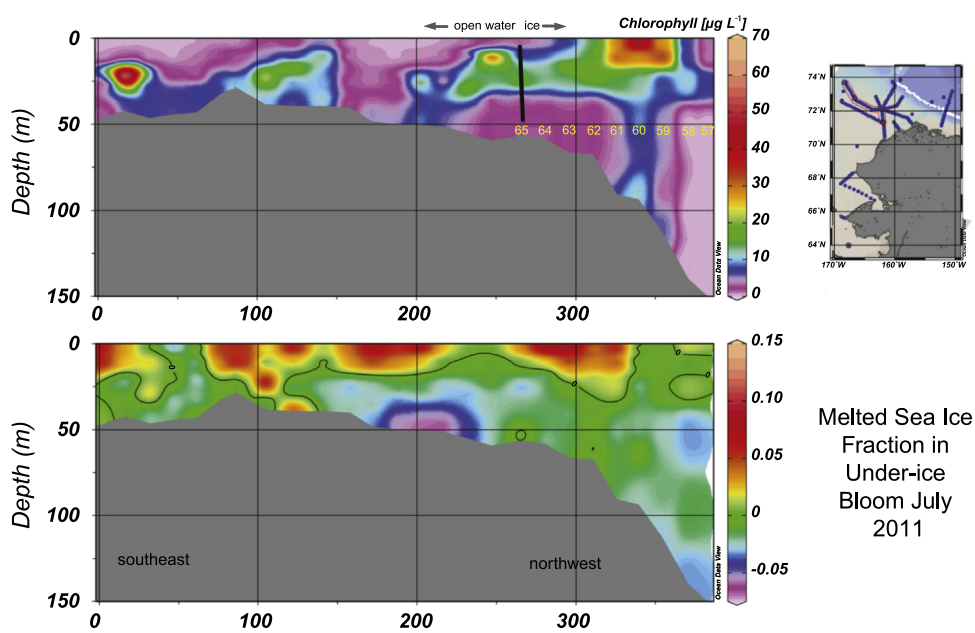

Fig. 5. Chlorophyll *a* (top panel) and sea ice melt fraction (bottom panel) for section into the under-ice bloom observed 4–8 July 2011. The section occupied is shown on the map inset, upper right, and is also shown in Fig. 3 (red and white circles). Numbers on the top panel indicate the location of the numbered stations located in Fig. 3. The transect orientation shown is (left to right) from southeast to northwest (0–400 km). Figure generated through Ocean Data View software, version 4 (Schlitzer, 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

retreat, it is plausible that an under-ice bloom could exhaust nutrients prior to initiation of a MIZ bloom, although in some areas of the Chukchi shelf, a continuous supply of nutrients through Bering Strait sustains high productivity throughout the seasonal cycle regardless of ice coverage (Walsh et al., 1989; Springer et al., 1996; Cooper et al., 1997; Grebmeier et al., 2015).

The presence of sea ice melt under seemingly solid ice, as shown in this study, argues that some microalgae from sea ice sources must be present in the waters underlying the ice, and that some of the production observed in this under-ice bloom is derived from production initiated in sea ice. More complete analysis of the evolution of sea ice algal communities in these early stages of melt in comparison to underlying pelagic phytoplankton is required before conclusions can be drawn about the significance of chlorophyll biomass under the ice as a driver of productivity in arctic marine systems.

Acknowledgments

This research was part of the NASA Impacts of Climate change on the Ecosystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) project with support from the NASA Cryospheric Sciences Program (Grant # NNX10AH71G to K. Frey, L. Cooper, and J. Grebmeier) and the NASA Ocean Biology and Biogeochemistry Program. Support from NOAA for the joint Russia-US Long-term Census of the Arctic (RUSLACA) program was also used for data analysis and interpretation and we also thank the Sitka Sound Science Center for support while in residence in Sitka. We thank Alynne Bayard for assistance with some of the graphical preparations and two anonymous reviewers who provided constructive suggestions to improve presentation of the study. The field component of this research would not have been possible without the tremendous support from the commanding officer, marine science technicians, crew, and officers of USCGC Healy on the HLY1101 mission to the Chukchi and Beaufort seas in June–July 2011. We also thank Holly Kelly for shipboard support. Data used in the NASA portion of the study are available from http://datadryad.org/resource/doi:10.5061/dryad.4dn793t6. Archived data from the other cruises are available from data archives at the Earth Observations Laboratory, University Corporation for Atmospheric Research and the Global Seawater Oxygen-18 Database.

References

Arrigo, K.R., Perovich, D.K., Pickart, R.S., Brown, Z.W., van Dijken, G.L., Lowry, K.E., Mills, M.M., Palmer, M.A., Balch, W.M., Bahr, F., Bates, N.R., Benitez-Nelson, C., Bowler, B., Brownlee, E., Ehn, J.K., Frey, K.E., Garley, R., Laney, S.R., Lubelczyk, L., Mathis, J., Matsuoka, A., Mitchell, B.G., Moore, G.W.K., Ortega-Retuerta, E., Pal, S., Polashenski, C.M., Reynolds, R.A., Schieber, B., Sosik, H.M., Stephens, M., Swift, J. H., 2012. Massive phytoplankton blooms under Arctic Sea ice. Science 336, 1408.

Arrigo, K.R., Perovich, D.K., Pickart, R.S., Brown, Z.W., van Dijken, G.L., Lowry, K.E., Mills, M.M., Palmer, M.A., Balch, W.M., Bates, N.R., Benitez-Nelson, C.R., Brownlee, E., Frey, K.E., Laney, S.R., Mathis, J., Matsuoka, A., Greg Mitchell, B., Moore, G.W.K., Reynolds, R.A., Sosik, H.M., Swift, J.H., 2014. Phytoplankton blooms beneath the sea ice in the Chukchi Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr. 105, 1–16. http://dx.doi.org/10.1016/j.dsr2.2014.03.018.

Balch, W.M., Bowler, B.C., Lubelczyk, L.C., Stevens Jr., M.W., 2014. Aerial extent, composition, bio-optics and biogeochemistry of a massive under-ice algal bloom in the Arctic. Deep Sea Res. Part II: Top. Stud. Oceanogr. 105, 42–58.

Bauch, D., Schlosser, P., Fairbanks, R.G., 1995. Freshwater balance and the sources of deep and bottom waters in the Arctic Ocean inferred from the distribution of $H_2{}^{18}O$. Prog. Oceanogr. 35, 53–80.

Chierici, M., Fransson, A., 2009. $CaCO_3$ saturation in the surface water of the Arctic Ocean: undersaturation in freshwater influenced shelves. Biogeosciences 6, 2421–2432.

Clement, J.L., Cooper, L.W., Grebmeier, J.M., 2004. Late winter water column and sea ice conditions in the northern Bering Sea. J. Geophys. Res. – Oceans 109, C03022, doi:03010.01029/02003JC002047, 002004.

Codispoti, L.A., Flagg, C., Kelly, V., Swift, J.H., 2005. Hydrographic conditions during the 2002 SBI process experiments. Deep Sea Res. Part II: Top. Stud. Oceanogr. 52 10.1916/j.dsr2.2005.10.007.

Cooper, L.W., Whitledge, T.E., Grebmeier, J.M., Weingartner, T., 1997. The nutrient, salinity, and stable oxygen isotope composition of Bering and Chukchi Seas waters in and near the Bering Strait. J. Geophys. Res. – Oceans 102, 12563–12573.

Cooper, L.W., Cota, G.F., Pomeroy, L.R., Grebmeier, J.M., Whitledge, T.E., 1999. Modification of NO, PO, and NO/PO during flow across the Bering and Chukchi shelves: implications for use as Arctic water mass tracers. J. Geophys. Res. – Oceans 104, 7827–7836.

Cooper, L.W., Benner, R., McClelland, J.W., Peterson, B.J., Holmes, R.M., Raymond, P. A., Hansell, D.A., Grebmeier, J.M., Codispoti, L.A., 2005. Linkages among runoff, dissolved organic carbon, and the stable isotope composition of seawater and other water mass indicators in the Arctic Ocean. J. Geophys. Res. – Biogeosci. 110, G02013, doi:1029/2005JG000031.

Cooper, L.W., Codispoti, L.A., Kelly, V., Sheffield, G., Grebmeier, J.M., 2006. The potential for using Little Diomede Island as a platform for observing environmental conditions in Bering Strait. Arctic 59, 129–141.

Cooper, L.W., McClelland, J.W., Holmes, R.M., Raymond, P.A., Gibson, J., Guay, C.K., Peterson, B.J., 2008. Flow-weighted values of runoff tracers ($\delta^{18}O$, DOC, Ba, alkalinity) from the six largest Arctic rivers. Geophys. Res. Lett. 35, L18606, doi: 18610.11029/12008GL035007.

Cooper, L.W., Sexson, M.G., Grebmeier, J.M., Gradinger, R., Mordy, C.W., 2013. Linkages between sea ice coverage, pelagic-benthic coupling, and the distribution of spectacled eiders: observations in March 2008, 2009, 2010 from the northern Bering Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr. 94, 31–43.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468.

Dittmar, T., Kattner, G., 2003. The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review. Marine Chem. 83, 103–120.

Ekwurzel, B., Schlosser, P., Mortlock, R.A., Fairbanks, R.G., Swift, J.H., 2001. River runoff, sea ice meltwater, and Pacific water distribution and mean residence times in the Arctic Ocean. J. Geophys. Res. – Oceans 106, 9075–9092.

Fernández-Méndez, M., Wenzhöfer, F., Peeken, I., Sørensen, H.L., Glud, R.N., Boetius, A., 2014. Composition, buoyancy regulation and fate of ice algal aggregates in the Central Arctic Ocean. PLoS One 9, e107452.

Fransson, A., Chierici, M., Miller, L.A., Carnat, G., Thomas, H., Shadwick, E.H., Pineault, S., Papakyriakou, T.M., 2013. Impact of sea ice processes on the carbonate system and 554 ocean acidification state at the ice-water interface of the Amundsen Gulf, Arctic Ocean. J. Geophys. Res. Oceans 118, 1–23. http://dx.doi.org/10.1002/2013JC009164.

Frey, K.E., Perovich, D.K., Light, B., 2011. The spatial distribution of solar radiation under a melting Arctic sea ice cover. Geophys. Res. Lett., 38. http://dx.doi.org/10.1029/2011gl049421.

Frey, K.E., Maslanik, J.A., Kinney, J.C., Maslowski, W., 2014. Recent variability in sea ice cover, age, and thickness in the Pacific Arctic Region. In: Grebmeier, J.M., Maslowski, W. (Eds.), The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment. Springer, pp. 31–63.

Grebmeier, J.M., Cooper, L.W., DeNiro, M.J., 1990. Oxygen isotopic composition of bottom seawater and tunicate cellulose used as indicators of water masses in the northern Bering and Chukchi Seas. Limnol. Oceanogr. 35, 1182–1195.

Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S.L., Arrigo, K.R., Blanchard, A. L., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kędra, M., Konar, B., Kuletz, K. J., Lee, S.H., Lovvorn, J.R., Norcross, B.L., Okkonen, S.R., 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Prog. Oceanogr. 136, 92–114.

Kattner, G., Lobbes, J.M., Fitznar, H.P., Engbrodt, R., Nöthig, E.M., Lara, R.J., 1999. Tracing dissolved organic substances and nutrients from the Lena River through Laptev Sea (Arctic). Marine Chem. 65, 25–39.

Khim, B.K., Krantz, D.E., Cooper, L.W., Grebmeier, J.M., 2003. Seasonal discharge of estuarine freshwater to the western Chukchi Sea shelf identified in stable isotope profiles of mollusk shells. J. Geophys. Res. 108, 3300–3309. http://dx.doi.org/10.1029/2003JC001816.

Laney, S.R., Sosik, H.M., 2014. Phytoplankton assemblage structure in and around a massive under-ice bloom in the Chukchi Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr. 105, 30–41. http://dx.doi.org/10.1016/j.dsr2.2014.03.012.

Li, W.K., McLaughlin, F.A., Lovejoy, C., Carmack, E.C., 2009. Smallest algae thrive as the Arctic Ocean freshens. Science 326 539-539.

Logvinova, C.L., Frey, K.E., Cooper, L.W. The potential role of sea ice melt in the distribution of chromophoric dissolved organic matter in the Chukchi and Beaufort Seas. Deep-Sea Res. II: Top. Stud. Oceanogr., this issue [doi: 10.1016/j.dsr2.xxxx.xx.xxx].

Lowry, K.E., van Dijken, G.L., Arrigo, K.R., 2014. Evidence of under-ice phytoplankton blooms in the Chukchi Sea from 1998 to 2012. Deep Sea Res. Part II: Top. Stud. Oceanogr. 105, 105–117.

Melnikov, I.A., Kolosova, E.G., Welch, H.E., Zhitina, L.S., 2002. Sea ice biological communities and nutrient dynamics in the Canada Basin of the Arctic Ocean. Deep Sea Res. Part I: Oceanogr. Res. Pap. 49, 1623–1649.

Morison, J., Kwok, R., Peralta-Ferriz, C., Alkire, M., Rigor, I., Andersen, R., Steele, M., 2012. Changing Arctic Ocean freshwater pathways. Nature 481, 66–70.

Münchow, A., Weingartner, T.J., Cooper, L.W., 1999. The summer hydrography and surface circulation of the East Siberian shelf Sea. J. Phys. Oceanogr. 29, 2167–2182.

Mundy, C., Gosselin, M., Ehn, J., Gratton, Y., Rossnagel, A., Barber, D.G., Martin, J., Tremblay, J.É., Palmer, M., Arrigo, K.R., 2009. Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea. Geophys. Res. Lett. 36, L17601. http://dx.doi.org/10.1029/2009GL038837.

Mundy, C.J., Gosselin, M., Gratton, Y., Brown, K., Galindo, V., Campbell, K., Levasseur, M., Barber, D., Papakyriakou, T., Bélanger, S., 2014. Role of environmental factors on phytoplankton bloom initiation under landfast sea ice in Resolute Passage, Canada. Mar. Ecol. Prog. Ser. 497, 39–49. http://dx.doi.org/10.3354/meps10587.

Paul, D., Skrzypek, G., Fórizs, I., 2007. Normalization of measured stable isotopic compositions to isotope reference scales – a review. Rapid Commun. Mass Spectrom. 21, 3006–3014.
Riedel, A., Michel, C., Gosselin, M., LeBlanc, B., 2008. Winter–spring dynamics in sea-ice carbon cycling in the coastal Arctic Ocean. J. Mar. Syst. 74, 918–932.
Robbins, L.L., Wynn, J.G., Lisle, J.T., Yates, K.K., Knorr, P.O., Byrne, R.H., Liu, X., Patsavas, M.C., Azetsu-Scott, K., Takahashi, T., 2013. Baseline monitoring of the Western Arctic Ocean estimates 20% of Canadian Basin surface waters are undersaturated with respect to aragonite. PLoS One 8, e73796.
Różańska, M., Poulin, M., Gosselin, M., 2008. Protist entrapment in newly formed sea ice in the Coastal Arctic Ocean. J. Mar. Syst. 74, 887–901.
Schlosser, P., Bauch, D., Fairbanks, R., Bönisch, G., 1994. Arctic river-runoff: mean residence time on the shelves and in the halocline. Deep-Sea Res. 41, 1053–1068.
Schlitzer, R., 2014. Ocean Data View, Version 4. 〈http://odv.awi.de〉.
Springer, A.M., McRoy, C.P., Flint, M.V., 1996. The Bering Sea Green Belt: shelf-edge processes and ecosystem production. Fish. Oceanogr. 5, 205–223.
Walsh, J.J., McRoy, C.P., Coachman, L.K., Goering, J.J., Nihoul, J.J., Whitledge, T.E., Blackburn, T.H., Parker, P.L., Wirick, C.D., Shuert, P.G., Grebmeier, J.M., Springer, A.M., Tripp, R.D., Hansell, D.A., Djenidi, S., Deleersnijder, E., Henricksen, K., Lund, K., Andersen, P., Müller-Karger, F.E., Dean, K., 1989. Carbon and nitrogen cycling within the Bering/Chukchi Seas: source regions for organic matter effecting AOU demands of the Arctic Ocean. Prog. Oceanogr. 22, 277–359.
Weingartner, T.J., Danielson, S., Sasaki, Y., Pavlov, V., Kulakov, M., 1999. The Siberian Coastal Current: a wind- and buoyancy-forced arctic coastal current. J. Geophys. Res. 104, 29697–29713.
Weingartner, T., Aagaard, K., Woodgate, R., Danielson, S., Sasaki, Y., Cavalieri, D., 2005. Circulation on the north central Chukchi Sea shelf. Deep Sea Res. Part II: Top. Stud. Oceanogr. 52, 3150–3174.
Woodgate, R.A., Weingartner, T.J., Lindsay, R., 2012. Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column. Geophys. Res. Lett. 39, L24603, doi: 24610.21029/22012GL054092, 052012.
Yamamoto-Kawai, M., McLaughlin, F., Carmack, E.C., Nishino, S., Shimada, K., 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt. Science 326, 1098–1100. http://dx.doi.org/10.1126/science1174190.

Please cite this article as: Cooper, L.W., et al., Variations in the proportions of melted sea ice and runoff in surface waters of the Chukchi Sea: A.... Deep-Sea Res. II (2016), http://dx.doi.org/10.1016/j.dsr2.2016.04.014