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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

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ABSTRACT

Retrospective analysis of apparent freshwater isotopic end-members through use of salinity–$\delta^{18}O$ 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

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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 δ^{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 δ^{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 δ^{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 δ^{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; δ^{18}O of $-21.35‰$) flowing through the Strait; this stable isotope end-member corresponds to the most up-to-date regressions of δ^{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 δ^{18}O value of $-1‰$ (Logvinova et al., 2016).

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 δ^{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.