Deep-Sea Research II 130 (2016) 88–99

Contents lists available at ScienceDirect

Deep-Sea Research II

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

Mass balance estimates of carbon export in different water masses of the Chukchi Sea shelf

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ARTICLE INFO

Available online 14 May 2016

Keywords:
Carbon export
Pelagic-benthic coupling
Phytoplankton
Chukchi
Sea ice

ABSTRACT

We construct mass-balance based estimates of carbon (C) export fractions from the water column across the Chukchi Sea shelf. Export is calculated as the difference between phytoplankton drawdown of dissolved inorganic C (DIC) and the accumulation of autochthonous particulate and dissolved organic C in the water column. Organic carbon (C_{org}) exports of $>50\%$ of DIC drawdown are ubiquitous across the shelf, even during, or shortly after, phytoplankton blooms, suggesting widespread and strong pelagic-benthic coupling. Export fractions on the shelf were generally greater in the less-productive Alaska Coastal Water than in the more productive Bering Shelf-Anadyr Water. Additionally, export fractions were greater in 2011 than in 2010, highlighting the significant spatial and inter-annual variability of the fate of C_{org} in this ecologically and biogeochemically important, and rapidly changing, ecosystem.

1. Introduction

The response of primary production to changes in sea ice cover is of central interest to the Arctic community (Schofield et al., 2010). Characterizing this response allows us to understand how climate change will influence Arctic marine ecosystems, as well as how the cycling of carbon (C) and nitrogen (N) in these systems will affect global C and N budgets. As an example, the Chukchi Sea shelf in the Pacific Arctic exhibited a 48% increase in net primary production (NPP) between 1998 and 2009 (Arrigo and van Dijken, 2011) (though see Yun et al., 2014 for evidence of lower primary production on the shelf in 2009). It has been suggested that more exposed open water, staying ice-free for longer, with greater biological productivity in the surface layer, leads to a greater air-sea flux of carbon dioxide (CO_2) (Bates and Mathis, 2009), and that any extra drawdown enhances the CO_2 sink, acting as a negative feedback on climate change.

Ultimately, however, any changes in net flux of CO_2 are only a significant feedback to climate change if the associated C removed from the atmosphere enters and remains in the deep ocean, where it is no longer in equilibrium exchange with the atmosphere, or is buried in the sediments. Even if primary production increases substantially on the shelf, if the resulting organic C is remineralized back to CO_2 in shallow waters and re-equilibrates with the atmosphere, the net effect on the C cycle is only an increase in the rate of ocean-atmosphere C cycling, but not an increase in the net oceanic storage of C. In the deep ocean, a fraction of C_{org} fixed by photosynthesis sinks below the mixed layer and is exported to depth, sequestering it from exchange with the atmosphere. The fraction of fixed C_{org} that is exported from the surface ocean through this 'biological pump' is a critical global determinant of the fate of anthropogenic CO_2 in the atmosphere (Ducklow et al., 2001).

On shallow (<150 m) continental shelves where the entire water column mixes in the winter due to sea ice formation, C_{org} export is not sequestered below the mixed layer. In shallow shelf

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http://dx.doi.org/10.1016/j.dsr2.2016.05.003
0967-0645/

systems, fixed C_{org} is either remineralized and exchanged with the atmosphere, accumulates in benthic sediments, or is transported off of the shelf. Many such continental shelves exhibit the capacity to "pump" atmospheric C to the deep ocean by advecting dense coastal C-rich water off the continental shelf, through a process known as the "continental shelf pump" (Tsunogai et al., 1999). There is evidence for an active continental shelf pump in the western Arctic Ocean, including the Chukchi Sea and East Siberian Sea shelves (Bates 2006; Anderson et al., 2010). Results from the Shelf-Basin Interactions (SBI) project show significant, but seasonally variable, rates of C export off the northeastern Chukchi Sea shelf (Moran et al., 2005; Lalande et al., 2007b; Lepore et al., 2007). Understanding the spatial variability of rates of C_{org} export from the vast productive Chukchi Sea shelf is critical to understanding the response of the C cycle to reductions in sea ice duration and extent in this region.

The Chukchi Sea is a shallow continental shelf sea located in the western Arctic Ocean, bounded on the southwest by the Chukotka Peninsula and on the southeast by northwestern Alaska. It has an average shelf depth of ~50 m (Hameedi, 1978), and there is a pronounced shelf-break that runs northwest to southeast, separating the Chukchi Sea shelf from the Canada Basin (Weingartner et al., 2005). Pacific water flows onto the shelf from the Bering Strait (Fig. 1), originating from three distinct sources. The first is the nutrient-rich water from the Gulf of Anadyr and the second is water from the central Bering Sea shelf. These two water masses flow through the western portion of the Bering Strait (Hansell et al., 1993; Cooper et al., 1997; Weingartner et al., 2005), and mix in the southern Chukchi Sea to form Bering Sea Water (BSW, Coachman et al., 1975). The third Pacific water source is Alaskan Coastal Water (ACW), which is warmer and fresher than BSW and lower in nutrients. It is advected northward by the Alaskan Coastal Current (ACC) and flows through the eastern portion of the Bering Strait predominantly in summer (Paquette and Bourque, 1974; Weingartner et al., 2005).

It is believed that the BSW and ACW progress northward in the Chukchi Sea predominantly along three main pathways. One of these pathways is the ACC (Fig. 1, shown in light green), which comprises ACW, and two of these pathways comprise BSW: a central branch and a western branch. In the central branch, BSW follows a pathway through the Central Channel (between Herald and Hanna shoals) and in the western branch, BSW flows through Hope Valley into Herald Canyon (Fig. 1, shown in dark blue). As described in Pickart et al. (2016) and shown in Fig. 1, some of the water in the western branch is diverted eastward north of Herald Shoal and joins the Central Channel branch. As this water encounters Hanna Shoal it then bifurcates and flows around each side of the shoal. In addition, some of the water in the Central Channel pathway appears to leak through gaps in the ridge between Hanna and Herald shoals. Ultimately much of the Pacific water entering through Bering Strait drains through Barrow Canyon, particularly during the summer months (Itoh et al., 2015; Gong and Pickart, 2015; Pickart et al., 2016). Notably, the middle of Barrow Canyon exhibits high benthic biomass (Grebmeier, 2012). This is the location where high-nutrient Pacific winter water exits the shelf in late-summer (Itoh et al., 2015) and also where wind-driven upwelling can bring this water back into the canyon from the Canada Basin (Mountain et al., 1976; Aagaard and Roach, 1990; Pickart et al., 2013). An eastward flowing shelf-break jet flows along the northern edge of the Chukchi Sea (Pickart et al., 2005), which can spawn eddies that transport organic carbon off the shelf (Mathis et al., 2007a).

Sea ice retreats from south to north across the shelf, beginning in May each year. From 1979 to 1998, sea ice remained over the northern portion of the Chukchi shelf in summer. Since then, however, the ice has regularly been retreating past the shelf-break each summer, and, since 2007, it has retreated fully or nearly-fully off the shelf each year. In the Chukchi Sea, the mean open water area has increased by 1000 km^2 per year over the last decade, and the duration of the open water season has also significantly increased (Brown and Arrigo, 2012; Frey et al. 2015). There is some evidence that these patterns of retreat are due to changes in annual mean heat flux through the Bering Strait (Shimada et al., 2006; Woodgate et al., 2012).

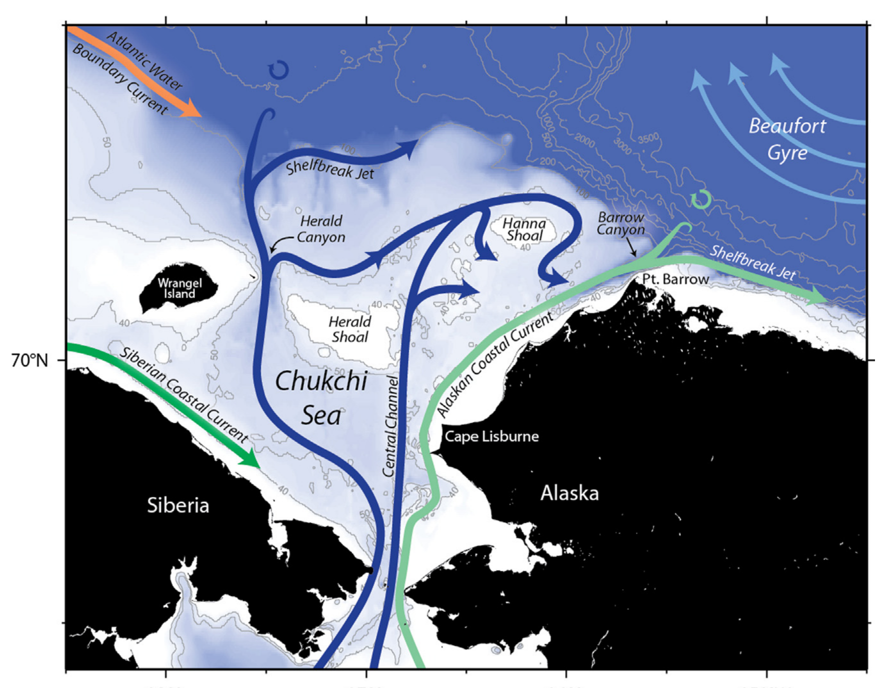

Fig. 1. Schematic circulation of the Chukchi Sea shelf region (after Brugler et al. 2014), including place names. Water enters the shelf through the Bering Strait. The Bering Sea Water (BSW) flow pathways, which progress across the shelf around Herald and Hanna Shoals, are shown in dark blue. The Alaska Coastal Current flow path, which follows the coast, is shown in light green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)