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Integrated assessment of the carbon budget in the southeastern Bering Sea

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ABSTRACT

During the primary field program for the Bering Ecosystem Study (2008–2010), independent seasonal estimates of net primary production (*NPP*), net community production (*NCP*), vertical export production (C_{exp}), and benthic carbon consumption (*BCC*) were used to construct a shelf-wide carbon budget for the southeastern Bering Sea. Here, we quantify the annual production, utilization, and transport of *NPP* for the southeastern shelf region of the Bering Sea (spatially partitioned into Outer, Middle, and Coastal Domains). We observed that approximately 25% and 30% of *NPP* on the shelf is exported horizontally from the Middle and Outer Domains, respectively. This horizontal transport was the dominant mode of carbon export in the Outer Domain, exceeding C_{exp} by more than 30 g C m^{-2} yr^{-1} (99 g C m^{-2} yr^{-1} compared to 67 g C m^{-2} yr^{-1}, respectively). In the Middle Domain, C_{exp} was more prominent than lateral transport (65 g C m^{-2} yr^{-1} and 46 g C m^{-2} yr^{-1}, respectively), and vertically exported carbon was more efficiently recycled in this Domain than in the Outer Domain (53% and 32% of C_{exp} respectively). In the Coastal Domain, lateral transport was a source of carbon to the bottom layer, with estimated input of carbon exceeding *NPP* by as much as 54 g C m^{-2} yr^{-1}. While the source of this additional carbon is unknown, one possible source is transport from the Middle Domain during wind events that induce coastal convergence. Overall, the combined carbon reservoir attributed to burial and transport in the Middle and Outer Domains is similar to a previous budget for this region (47%; Walsh and McRoy, 1986), although some qualitative differences are apparent. The data presented here indicate a more pelagic character in the Outer Domain relative to the Middle Domain, and that the Middle and Coastal Domain carbon budgets are balanced only when combined.

1. Introduction

The southeastern Bering Sea is one of the most productive shelf areas of the global ocean, with daily rates of net primary production (*NPP*) during ice edge blooms exceeding ~10 g C m^{-2} d^{-1} under optimal growth conditions (Niebauer et al., 1995; Lomas et al., 2012). The fate of this production has significant consequences for the attendant food web, and the energy provided by primary production sustains both pelagic and benthic commercial fisheries. However, varying physical and climatic conditions can favor energy accumulation in either the pelagic or the benthic compartments, with significant consequences for commercial populations (Hunt et al., 2002, 2011; Hunt and Stabeno, 2002). Remineralization of detrital

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production in the subsurface water column and underlying sediments results in the seasonal accumulation of carbon dioxide (CO_2) in bottom waters, sharply reducing seawater pH during the highly productive spring–summer period (Mathis et al., 2011a, b). This process increases the vulnerability to ocean acidification processes via the uptake of anthropogenic CO_2, and has been observed to result in undersaturation of important calcium carbonate ($CaCO_3$) minerals critical for shell-building organisms in both the Bering and Chukchi Seas (Bates et al., 2009; Mathis et al., 2011a, b; Cross et al., 2013).

Although it is clear that the balance of production and export is critical to understanding the functioning of the Bering Sea ecosystem, some portions of the carbon cycle remain poorly understood. For example, a paucity of data from near-coastal regions has resulted in limited and often conflicting patterns in temporal variability and the balance of primary production and export (e.g., Lomas et al., 2012; Moran et al., 2012). Other aspects of the carbon cycle have only recently gained attention, such as microzooplankton herbivory and surface bacterial remineralization loops (Moran et al., 2012; Olson and Strom, 2002; Sherr et al., 2013; Stoecker et al., in press-a,b). Recent physical and biogeochemical data has also provided some evidence that organic carbon losses due to lateral transport may be more complex than previously assumed (Danielson et al., 2012a, 2012b; Baumann et al., 2013a, 2013b).

In the last five years, oceanographic expeditions as part of the multidisciplinary Bering Sea Project provided an opportunity to evaluate independent estimates of the various rate and budget components of the Bering Sea shelf carbon cycle as a whole, and thereby to examine some of these unresolved carbon sinks. In this study, we provide a synthesis of net primary production (*NPP*), net community production (*NCP*), vertical export production (C_{exp}), and benthic carbon consumption (*BCC*) estimates to construct a budget for determining the fate of organic carbon production through heterotrophic utilization and transport across the southeastern Bering Sea shelf.

2. Methods

2.1. Sample collection

Physical, chemical, and biological measurements for the water column and sediments were collected as part of the Bering Sea Project during the following cruises: USCGC *Healy* during spring (April/May) of 2008 and 2009, and summer (July) of 2008; R/V *Knorr* in summer (June/July) of 2009; and R/V *Thomas G. Thompson* during late spring (May/June) and early summer (June/July) of 2010. Hydrographic (CTD) stations were occupied along two east–west transect lines (i.e., NP and CN lines) and one north–south transect along the 70 m isobath (i.e., 70 M) as well as in several regions of opportunity (Fig. 1). Biological and sediment studies were conducted at a subset of these stations. At the beginning of each spring cruise, sea ice cover was near 100% at all stations except for the southern stations of the 70 M line, which were sea-ice free when sampled during spring in all years. During spring of 2010, the timing of the occupation of some stations, as well as the spatial extent of sampling, was limited by the ice breaking capability of R/V *Thompson*. Some inshore stations were sampled later than usual during spring to allow for some sea ice melt. During summer observations, the entire Bering Sea shelf was sea-ice free for all years.

In order to facilitate a common spatial reference for the participants in the Bering Sea Project, the study region was divided into 16 standardized domains based on hydrographic structure, circulation patterns, and macrofaunal population distribution (Ortiz et al., 2012, Harvey and Sigler, 2013). Data included in this study were collected in Region 4, which we denote as the Southern Outer Domain; Regions 3 and 6, which we denote as the southern central domain; and Regions 2 and 7, which we denote as the Southern Coastal Domain (Fig. 1). Our domains comprise both the southern and the central portions of the eastern shelf according to the project definitions. However, a proviso to the definition of spatial domains is that the boundary between the southern and central shelves described by Ortiz et al. (2012) was included to distinguish the spatial area covered by historical groundfish surveys and has no hydrographic or biogeochemical context. In the absence of a strong boundary between the southern and central shelves, we combined these two areas in our synthesis effort. This study thus assumes that the northern boundary between the southeastern and northeastern portions of the shelves is a cross-shelf jet occurring in the vicinity of Nunivak Island (Danielson et al., 2011; Ortiz et al., 2012). Near the shelf break, biological regimes in the vicinity of the Pribilof Islands also led to the distinction of an elliptical domain (e.g., Cianelli et al., 2004; Hunt et al., 2008). Because of the unique processes occurring here, we have not included data collected in the Pribilof Domain (Region 5).

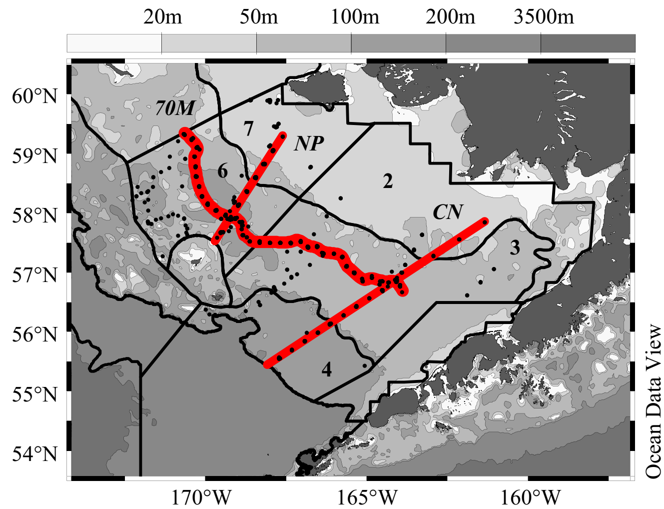

Fig. 1. A map of the southeastern Bering Sea shelf indicating sampling locations (dots) and major regions of the Bering Sea Shelf as defined by the Bering Sea Project (numbered regions delineated with dark black outlines). Bathymetry is shaded according to depth. Repeat hydrographic lines include the CN Line, the NP Line, and the 70 M Line.

2.2. Sample analysis

2.2.1. Water column rate measurements

2.2.1.1. Net primary production (NPP). Samples for ^{14}C incubations were collected roughly every other day from depths approximately ~1.5%, ~5%, ~9%, ~17%, ~33%, ~55%, and ~100% light levels of surface incident photosynthetically active radiation (PAR) (Lomas et al., 2012). Light depths were determined by analysis of PAR profiles on the CTD downcast generated using an calibrated Biospherical Instruments PAR sensor. Net primary production (*NPP*) rates were calculated from the autotrophic incorporation of $NaH^{14}CO_3^-$ into particulate organic matter over a 24-h simulated in situ incubation using the ratio of added radiocarbon to total inorganic carbon present (Parsons et al., 1984; Lomas et al., 2012). Daily volumetric rates of *NPP* were integrated to the deepest sample depth (i.e., ~1.5% light level) and corrected for passive incorporation of $NaH^{14}CO_3^-$ using a dark control and the total added activity for the profile measured at the start of the incubation.