

## RESEARCH LETTER

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## Key Points:

- Less than 5% of the POC produced by primary production sank to the seafloor of the Amundsen Sea
- Most of the carbon drawn into the subsurface by the biological pump was transported off the shelf by northward currents
- The intrusion of Circumpolar Deep Water and the lack of bottom water formation reduce carbon sequestration efficiency

## Supporting Information:

- Supporting Information S1

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## Evidence of minimal carbon sequestration in the productive Amundsen Sea polynya

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**Abstract** The Amundsen Sea polynya (ASP) is reportedly the most productive among the coastal polynyas around Antarctica. However, observational constraints limit our understanding of the biological pump and carbon cycle in the ASP. We measured various carbon-related parameters such as primary production, bacterial production, sinking flux of particulate organic carbon (POC), and accumulation of organic carbon in the sediment as well as hydrographic parameters during field observations and by instrument moorings. Over 95% of the photosynthetically produced POC was converted to suspended POC and/or dissolved carbon forms in the upper ~400 m layer. We postulate that most of the carbon transported to the water column by the biological pump in the ASP was flushed out of the shelf without being sequestered for long-term storage in sediments. Lack of bottom water formation due to intrusion of Circumpolar Deep Water in the lower layer reduces carbon sequestration efficiency.

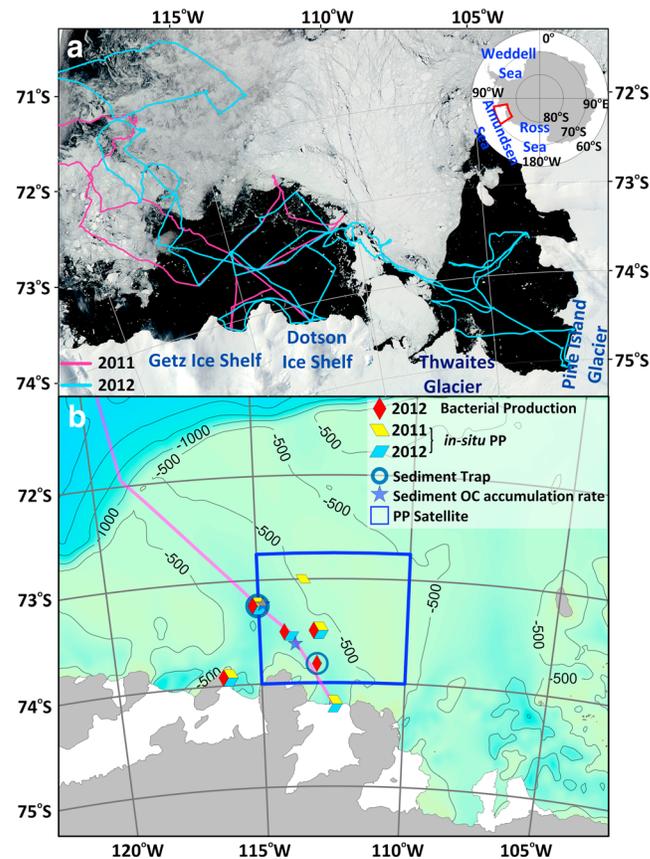
### 1. Introduction

Polynyas around Antarctica are known for their high primary production (PP), amounting to 96 TgC yr<sup>-1</sup> [Arrigo and van Dijken, 2003]. Previous studies have suggested that polynyas are a sink for atmospheric CO<sub>2</sub> [Arrigo et al., 2008a] as a result of high biological production in the austral summer and sea ice formation during winter. The generally accepted notion is that the atmospheric CO<sub>2</sub> absorbed by high PP is subsequently sequestered via bottom water formation around Antarctica [Arrigo et al., 2008b]. The Amundsen Sea polynya (ASP) is reportedly the most productive among the polynyas around Antarctica [Arrigo and van Dijken, 2003]. However, observational constraints limit our understanding of the fate of absorbed atmospheric CO<sub>2</sub> beyond the point of carbon fixation. It is unclear whether the absorbed carbon is sequestered in the local sediment or elsewhere in the ocean's interior.

We have been conducting field campaigns in the ASP and adjacent sea ice areas annually or biennially since the austral summer of 2010/2011. We obtained a variety of biogeochemical data including in situ PP, net community production (NCP), bacterial secondary production (BP), and year-round particulate organic carbon (POC) flux by time series sediment trap moorings, as well as total oxygen uptake rate and organic carbon accumulation rate in the sediments of the ASP (Figure 1). Hydrographic data were also obtained from LADCP (Lowered Acoustic Doppler Current Profiler) casts and year-round ADCP moorings. Some of these results have been described elsewhere [e.g., Meredith et al., 2016]. One of our research objectives was to understand the biological pump system currently operating in the Amundsen Sea and the fate of photosynthetically produced organic carbon, based on our POC flux results and other published results. This paper combines biogeochemical observations with an understanding of the unique water circulation in the Amundsen Sea in order to examine carbon sequestration efficiency in a productive polynya environment. We also provide implications of our findings on carbon sequestration in the polynyas around Antarctica, most of which have not been extensively studied yet.

### 2. Materials and Methods

We report here the results of the first two field campaigns in the ASP and adjacent sea ice areas during the austral summers aboard the IBRV *Araon*, as well as instrument moorings (Figure 1). The first cruise in the



**Figure 1.** Map of the study area showing the ship tracks and sea ice distribution in the Amundsen Sea (top), and locations of measurements and instrument moorings, the region for which satellite-based PP was estimated, and a transect for which temperature contours are drawn in Figure 3 (bottom). The MODIS Aqua satellite image, taken on 15 February 2012, was originally downloaded from NASA "Rapid Response"/LANCE.

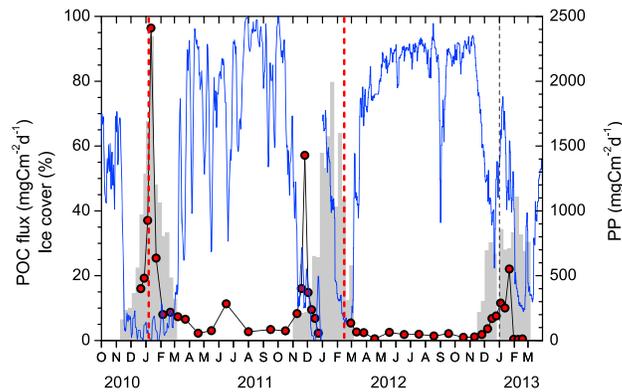
[Ducklow *et al.*, 2015] with a PPS 3/3 24S sediment trap (Technicap) from 18 December 2010 to 4 January 2012. Different trap designs or mooring methods may cause different flux behavior in local flow fields in the upper 250–300 m, yielding different trapping efficiencies in reference to the  $^{238}\text{U}$ - $^{234}\text{Th}$  disequilibrium method [Buesseler *et al.*, 2010]. However, the current speed monitored at 2 m below the trap was  $6.0 \pm 3.0 \text{ cm s}^{-1}$  with monthly maximum values smaller than  $19 \text{ cm s}^{-1}$  from February 2012 to March 2013, potentially minimizing the flow effect.

The net PP over the summers was estimated using the VGPM (vertically generalized production model) algorithm from the MODIS (Moderate Resolution Imaging Spectroradiometer) Level 3 standard mapped images (8 day composite, 4 km resolution) of chlorophyll *a*, sea surface temperature, and photosynthetically active radiation (NASA Goddard Space Flight Center) [Behrenfeld and Falkowski, 1997]. For in situ PP measurements, carbon uptake rate was determined in situ using a  $^{13}\text{C}$ - $^{15}\text{N}$  dual isotope tracer technique during the cruises [Lee *et al.*, 2012; B. K. Kim *et al.*, 2015]. The NCP was estimated from underway measurements of the ratio of dissolved oxygen and argon gases ( $\Delta\text{O}_2/\text{Ar}$ ) and other environmental parameters during each cruise [Hahm *et al.*, 2014]. A more detailed discussion of the methodology can be found in the supporting information [Lee *et al.*, 2012; Hahm *et al.*, 2014; B. K. Kim *et al.*, 2015; M. Kim *et al.*, 2015].

Yager *et al.* [2016] recently published a comprehensive set of data obtained from the U.S. ASPIRE project (Amundsen Sea Polynya International Research Expedition) [Yager *et al.*, 2012]. The U.S. ASPIRE project examined carbon-related parameters in the ASP from 13 December 2010 to 8 January 2011, a time frame that overlapped our first cruise.

ASP was conducted from 31 December 2010 to 8 January 2011. This period corresponded to rapid development of a phytoplankton bloom to a peak in early January, based on remotely sensed chlorophyll *a* data (Figure 2). The second cruise in the ASP was conducted 11–19 February 2012, when the phytoplankton bloom was declining. Vertical measurements of temperature, salinity, and currents were taken with a conductivity-temperature-depth (SeaBird Electronics SBE 911+) and an LADCP (300 kHz, Teledyne RDI).

Sinking particles for the POC flux were collected using a sediment trap (McLane PARFLUX) at 410 m from 15 February 2012 to 20 February 2013 in the central polynya (73.28°S, 114.97°W, 830 m water depth; Figure 1). POC flux was calculated from gravimetric determination of total mass flux and organic carbon content. Organic carbon content was determined as the difference between total carbon and inorganic carbon, which were analyzed using a Carlo-Erba elemental analyzer and a UIC coulometrics carbon analyzer, respectively [M. Kim *et al.*, 2015]. Sinking particles were previously collected at 350 m in the central polynya (73.82°S, 113.07°W, 785 m water depth; Figure 1)



**Figure 2.** POC flux in the Amundsen Sea polynya (red dots), and the satellite-based estimate of net primary production in the corresponding time in the central polynya (gray columns). POC flux data from December 2010 to January 2012 are from Ducklow et al. [2015]. Thin blue solid line indicates the percent sea ice concentration at each trap site. Vertical dashed lines indicate the time of each field expedition of about 9 days within the Amundsen Sea polynya.

**3. Results**

PP determined in situ by the <sup>13</sup>C isotope tracer technique in the ASP was 2200 ± 1400 mgC m<sup>-2</sup>d<sup>-1</sup> in 2010/2011 (peak bloom) and 250 ± 110 mgC m<sup>-2</sup>d<sup>-1</sup> in 2011/2012 (declining bloom) (Table 1) [Lee et al., 2012]. This variability may have been caused by measurements at different stages of the phytoplankton bloom, in addition to potential interannual variability [DeJong et al., 2017]. The in situ PP at the peak of the bloom (2200 mgC m<sup>-2</sup>d<sup>-1</sup>) in 2010/2011 corresponded well with the timing of the peak value of the satellite-based estimate of net PP (~2400 mgC m<sup>-2</sup>d<sup>-1</sup>; Figure 2).

Historical data of the satellite-based phytoplankton bloom in the ASP indicate that the bloom typically ends in late February (February 23 ± 5 d) [Arrigo et al., 2012]. Hence, the results obtained 11–19 February 2011/2012 provided an opportunity to examine the response of the polynya to the decline of the phytoplankton bloom. The PP values (250 ± 110 mgC m<sup>-2</sup>d<sup>-1</sup>) measured during the declining bloom were also similar to the satellite-based estimate (Figure 2) but were much lower than those in 2010/2011 (Table 1).

The average NCP values estimated from the ratio of dissolved oxygen and argon gases (ΔO<sub>2</sub>/Ar) in the mixed layer of the ASP were 1020 mgC m<sup>-2</sup>d<sup>-1</sup> in 2010/2011 and 200 mgC m<sup>-2</sup>d<sup>-1</sup> in 2011/2012. The NCP values (200 ± 120 mgC m<sup>-2</sup>d<sup>-1</sup>) in 2011/2012 were much lower than the preceding summer yet indicate that the ASP remained a net autotrophic system even after the significant decline in the bloom. The NCP values

**Table 1.** Primary Production, NCP, Bacterial Production/Respiration, Sinking POC Flux to ~400 m, Benthic Organic Carbon Remineralization Rate, and Organic Carbon Accumulation Rate in the ASP<sup>a</sup>

	December–January 2010/2011	February 2011/2012	2012/2013
Primary production			
<sup>13</sup> C uptake <sup>b</sup>	2200 ± 1400	250 ± 110	
Satellite <sup>c</sup>	990 ± 590	1050 ± 550	780 ± 130
NCP by ΔO <sub>2</sub> /Ar <sup>d</sup>	1020 ± 680	200 ± 120	
Bacterial production (respiration) <sup>e</sup>		130 ± 53 (800–2040)	
Bacterial respiration in 50–350 m layer <sup>f</sup>	180–1390		
POC flux in summer (sediment trap) <sup>g</sup>	25 <sup>h</sup>	15	7.2
Benthic OC remineralization <sup>i</sup>		25	
Accumulation in sediment <sup>j</sup>		2.7 ± 0.8	

<sup>a</sup>All values are presented in mgC m<sup>-2</sup>d<sup>-1</sup>.

<sup>b</sup>The 2010/2011 data are from Lee et al. [2012].

<sup>c</sup>An average value (±standard deviation) of 8 day data points (n = 16) from November to February by the Behrenfeld and Falkowski algorithm [Behrenfeld and Falkowski, 1997], averaged over the square, 115–110°W, 72.75–74.0°S (see text for detail and Figure 1).

<sup>d</sup>Averages (±standard deviations) of underway measurements in the ASP, from Hahn et al. [2014].

<sup>e</sup>These values were integrated over the surface mixed layer. BP values in 2011/2012 were recalculated from Hyun et al. [2016]. Bacterial respiration values were estimated from BP and bacterial growth efficiency of 0.06–0.14 [Carlson et al., 1999; Yager et al., 2012].

<sup>f</sup>These values were from Williams et al. [2016] and Ducklow et al. [2015].

<sup>g</sup>An average of POC flux from November to February (see text and Figure 2). Note that sampling coverage in 2011/2012 was incomplete.

<sup>h</sup>Data from Ducklow et al. [2015].

<sup>i</sup>Benthic organic carbon remineralization was estimated from the sediment oxygen demand [S.-H. Kim et al., 2016].

<sup>j</sup>POC accumulation rate was from M. Kim et al. [2016].

correspond to 71% and 21% of the satellite-based PP values at the corresponding time in 2010/2011 and 2011/2012, respectively. Bacterial secondary production (BP) integrated over the surface mixed layer (approximately 40 m) was  $130 \pm 53 \text{ mgC m}^{-2}\text{d}^{-1}$  ( $n = 4$ ) in 2011/2012 in the central polynya (Table 1) [Kim *et al.*, 2016]. These values correspond to a bacterial respiration of 800–2040  $\text{mgC m}^{-2}\text{d}^{-1}$  based on a bacterial growth efficiency of 0.06–0.14 [Carlson *et al.*, 1999; Yager *et al.*, 2012]. The bacterial respiration rate in the declining bloom, even higher than the PP values, implied active bacterial utilization of the accumulated organic carbon during the bloom [Hyun *et al.*, 2016].

The seasonal evolution of PP in the surface water was reflected in the flux of sinking POC (Figure 2) [Ducklow *et al.*, 2015]. Temporal variation in POC flux closely followed that of the satellite-based estimates of net PP during the summer of 2010/2011. After the termination of the bloom, POC flux remained low (mostly  $<5 \text{ mgC m}^{-2}\text{d}^{-1}$ ) until the initiation of the next bloom in the following summer. During the summer of 2011/2012, the POC flux started to increase in late November, reaching about 60% of the peak value in 2010/2011 and then decreased to almost zero by late December 2011. Unfortunately, there are no data for January and the first half of February 2012 when the satellite-based net PP data revealed a series of peaks. During the summer of 2012/2013, POC flux increased in December to the peak value in mid-January and then precipitously decreased to very low values. The POC flux integrated over the summer of 2012/2013 was notably lower than that of 2010/2011 (Figure 2).

## 4. Discussion

### 4.1. Biological Carbon Pump in the ASP

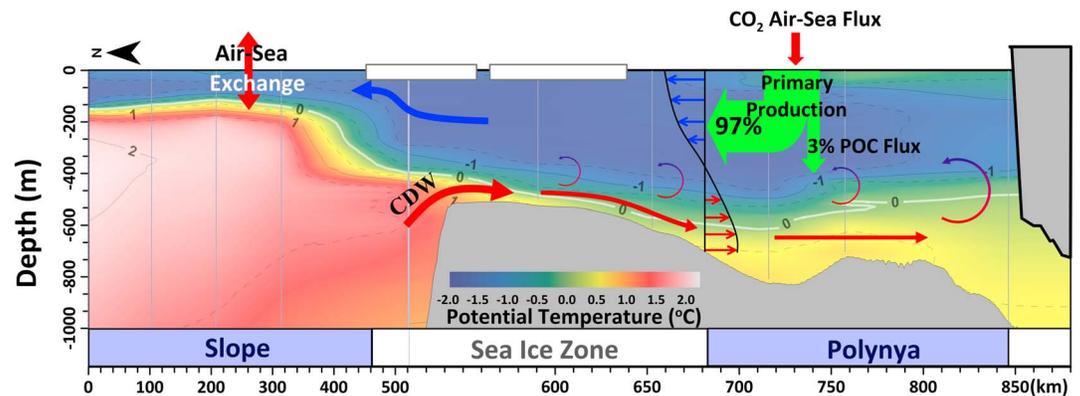
High PP suggested by satellite observations in the ASP was consistent with our in situ measurements. Considerable amounts of in situ PP and NCP were also observed during the second cruise. Based on a comprehensive set of data, Yager *et al.* [2016] showed that the ASP was an efficient export system. Estimated carbon export varied between negative values (meaning import) and  $900 \text{ mgC m}^{-2}\text{d}^{-1}$  [Yager *et al.*, 2016]. Sinking POC flux determined by short-term deployment of floating traps from 31 December 2010 to 3 January 2011 at 60 m and 150 m was 320 and  $32 \text{ mgC m}^{-2}\text{d}^{-1}$ , respectively [Ducklow *et al.*, 2015].

Despite the high PP, only a small fraction of the produced POC reached the trap depth [Weston *et al.*, 2013; Ducklow *et al.*, 2015]. Observed POC flux at a depth of  $\sim 400$  m corresponded to 1–2.5% of PP over the three summers (Table 1). This finding suggests that the majority of the POC exported from the surface mixed layer was converted to nonsinking forms such as fine suspended POC and/or dissolved carbon forms, either dissolved inorganic carbon (DIC) or dissolved organic carbon (DOC), in the water column before reaching the bottom. Possible factors that influence POC flux include bacterial respiration. Ducklow *et al.* [2015] showed that bacterial respiration in the 50–350 m depth interval was  $180\text{--}1390 \text{ mgC m}^{-2}\text{d}^{-1}$  during the summer of 2010/2011 and was enough to account for the decrease in the observed POC flux in the corresponding layer. High attenuation in POC flux may be related to the dominance of *Phaeocystis antarctica* among primary producers [Reigstad and Wassmann, 2007; Lee *et al.*, 2016].

Low sinking POC flux results were consistent with the observations in the underlying sediment. Benthic organic carbon remineralization, estimated from the sediment oxygen demand that was determined during the 2011/2012 expedition, was  $25 \text{ mgC m}^{-2}\text{d}^{-1}$  [S.-H. Kim *et al.*, 2016]. This value was comparable to the sinking POC flux. High-resolution radiocarbon analysis of organic matter in the upper 20 cm sediment at two locations in and around the ASP revealed that the organic carbon accumulation rate was about  $1.0 \pm 0.3 \text{ gC m}^{-2} \text{ year}^{-1}$  (equivalent to  $2.7 \pm 0.8 \text{ mgC m}^{-2}\text{d}^{-1}$ , which was  $<1\%$  of PP) for the last few thousand years [M. Kim *et al.*, 2016].

### 4.2. Fate of Carbon Exported From the Surface Mixed Layer

The ASP acts as an efficient net autotrophic system if we consider the air-sea boundary. The surface water  $\text{pCO}_2$ , determined by an underway measurement system, was considerably lower in the ASP than outside the polynya during the ASPIRE expedition in 2010/2011 [Mu *et al.*, 2014]. Low surface water  $\text{pCO}_2$  would facilitate absorption of atmospheric  $\text{CO}_2$ . Absorption of atmospheric  $\text{CO}_2$  in the austral summer and subsequent sea ice formation that blocks air-sea gas exchange makes the ASP seemingly an efficient sink of atmospheric  $\text{CO}_2$ . Yager *et al.* [1995] proposed a “rectification” hypothesis for seasonally ice-covered regions in order to emphasize the role of sea ice cover in retaining the absorbed  $\text{CO}_2$ : sea ice hinders escape of  $\text{CO}_2$  to the



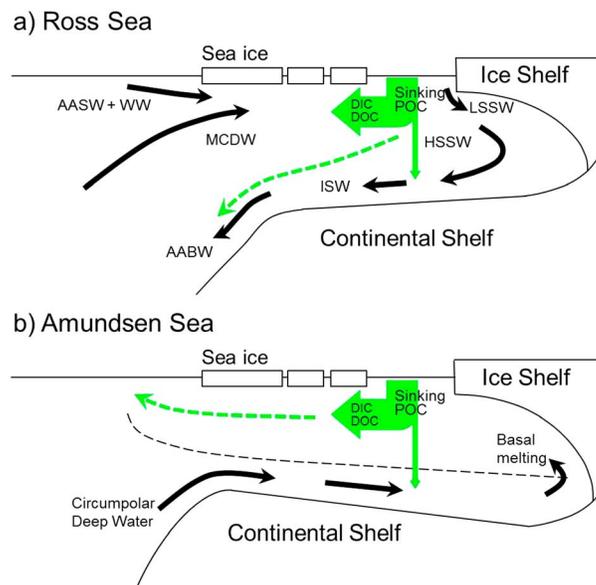
**Figure 3.** A schematic diagram of carbon flow in the Amundsen Sea overlain on top of potential temperature distribution along a cross-shelf transect indicated in Figure 1. Potential temperature cross section during the 2012 cruise was redrawn from Kim *et al.* [2017]. Note that the horizontal scale of the off shelf region (0–500 km) is shrunk as compared to the shelf region. The thick red and blue arrows indicate flow path of Circumpolar Deep Water (CDW) and the water in the upper layer leaving the shelf, respectively. Small arrows arranged along the vertical line are schematic representation of the currents obtained from ADCP moorings within Dotson trough [Ha *et al.*, 2014].

atmosphere during the respiration-dominant winter season, hence “rectifying” the oscillation of CO<sub>2</sub> exchange between the sea and the atmosphere. They suggested that the atmospheric carbon absorbed during the sea ice free summer is either stored in the local sediments or transported off-shelf to the adjacent deep ocean in the sea ice-covered seasons. In the ASP, because organic carbon is not stored efficiently in the underlying sediments [M. Kim *et al.*, 2016; S.-H. Kim *et al.*, 2016], the absorbed atmospheric CO<sub>2</sub> should be transported off the Amundsen shelf. In this sense, water circulation is critical in deciding the fate of carbon in the water column.

Because of the role of warm Circumpolar Deep Water (CDW) in melting the ice shelves in the Amundsen Sea, intrusion of CDW and behavior of modified CDW in the bottom layer have been examined in several studies [e.g., Wahlin *et al.*, 2010, 2012]. An analysis of moored ADCP data obtained near the boundary of the Amundsen shelf revealed that the inflow of CDW was approximately 0.34 sverdrup (Sv) along the eastern flank of Dotson trough below 360 m depth [Wahlin *et al.*, 2010; Ha *et al.*, 2014]. This water flux would be enough to overturn the water on the Amundsen shelf within a year [Wahlin *et al.*, 2016]. Approximately one third of the incoming CDW leaves the shelf through the western flank of Dotson trough [Ha *et al.*, 2014]. The intruding CDW flows to the inner shelf and helps to melt the ice shelves, thus becoming buoyant [Wahlin *et al.*, 2012]. Ekman pumping was also suggested to cause mixing between CDW and the overlying layer [Kim *et al.*, 2017].

A study of surface currents based on remotely sensed wind and sea ice velocity and concentration in the Amundsen Sea suggested a prevailing westward current at the surface with higher speeds near the coast [Kim *et al.*, 2017]. However, water circulation in the upper layer (i.e., subsurface to a depth of about 400 m) is not clearly understood. Results from four ADCP moorings within Dotson trough and LADCP results obtained during the field observations showed dominant northward flows in the upper layer [Ha *et al.*, 2014].

The unique physical setting of the Amundsen shelf facilitates flushing of the water in the upper layer off the shelf. The water of the upper layer above the sediment trap depth contains carbon that was absorbed from the atmosphere, transported by, and released from the sinking POC. Once the carbon-laden water exits the Amundsen shelf, it is likely to be spread and entrained into a relatively thin layer of water above the CDW (Figure 3). The water is subsequently subject to further CO<sub>2</sub> exchange; thus, the high PP in the surface ASP does not likely result in carbon sequestration to the deep interior. A potential consequence would be that the high concentration of DIC in the water may restrict further CO<sub>2</sub> absorption north of the sea ice zone, where photosynthetic activity is known to be relatively low even in December (0.5–1.0 gC m<sup>-2</sup>d<sup>-1</sup>) [Arrigo *et al.*, 1998]. A modeling study that examined the transport of meltwater from the ice shelves implied westward coastal flow, suggesting that more than 50% of the meltwater from the Getz Ice Shelf reaches the Ross Sea [Nakayama *et al.*, 2014]. How much of the absorbed



**Figure 4.** Schematics of water circulation and carbon flow in two contrasting environments: (a) the Ross Sea and (b) the Amundsen Sea. Water circulation in the Ross Sea and the Amundsen Sea was adopted from Sweeney [2003] and Petty *et al.* [2013], respectively. Green dashed arrows indicate conjectured carbon flow along the water flow. AASW: Antarctic Surface Water, WW: Winter Water, LSSW: Low Salinity Shelf Water, HSSW: High Salinity Shelf Water, ISW: Ice Shelf Water, AABW: Antarctic Bottom Water, and MCDW: Modified Circumpolar Deep Water.

Recently, a study reported DOC enrichment in dense shelf waters in the Ross Sea, which is ultimately sequestered into bottom waters [Bercovici *et al.*, 2017]. Water circulation on the Amundsen shelf is different from the Ross Sea in terms of bottom water formation [Jenkins *et al.*, 2016]. A similar contrast in water circulation between the Amundsen Sea and the Weddell Sea, where bottom water formation occurs, was described in Petty *et al.* [2013]. The schematics of carbon transport processes in the two contrasting environments are presented in Figure 4. Unlike the Ross Sea and the Weddell Sea, the Amundsen Sea lacks the means to transport carbon to the ocean interior. The continental shelf carbon pump is a process transporting DOC and DIC into the ocean interior from productive continental shelves [Tsunogai *et al.*, 1999; Thomas *et al.*, 2004]. For efficient carbon sequestration in polynyas, the continental shelf pump (i.e., shelf water formation that is dense enough to sink to the ocean's deep interior transporting carbon with it) should be aligned with the "rectification" effect by sea ice. The lack of a mechanism to transport the absorbed carbon to the ocean's interior dramatically reduces the sequestration efficiency of the biological pump system on the Amundsen shelf.

Water circulation within and surrounding Antarctic polynyas will eventually determine the fate of the absorbed  $\text{CO}_2$  in the polynyas (Figure 4). The continental shelves of Antarctica can be categorized into two groups based on water temperature near the seabed: Amundsen Sea-like and Weddell Sea-like (see Figure 1 of Petty *et al.*, 2013). There are three prominent regions where bottom water potential temperature is lower than  $-1.0^\circ\text{C}$ : the Ross Sea, the Weddell Sea, and around Prydz Bay. The Ross Sea polynya and the Ronne Ice Shelf polynya in the Weddell Sea account for over 60% of the total PP in the 37 identified polynyas around Antarctica [Arrigo and van Dijken, 2003], and these two polynyas are known as the sites of major bottom water formation [Ohshima *et al.*, 2013]. However, the polynyas in the west Antarctic similar to the ASP are influenced by CDW intrusion onto the shelf [Pritchard *et al.*, 2012; Petty *et al.*, 2013] and do not likely sequester atmospheric carbon into the deep interior of the Southern Ocean. These polynyas in the west Antarctic (between the Hull Bay polynya and the Marguerite Bay polynya) account for about 14% of the total PP in the Antarctic polynyas [Arrigo and van Dijken, 2003]. As seen in the ASP case, the role of polynyas in carbon cycling should be understood in conjunction with the unique qualities of the Antarctic shelf-slope system [Collier *et al.*, 2000] and the water circulation system that includes exchanges with the Southern Ocean [Jacobs, 1991].

carbon in the upper layer is transported to the Ross Sea and what fraction of it is incorporated into the Antarctic Bottom Water are future study subjects.

#### 4.3. Carbon Sequestration in the Antarctic Polynyas: Amundsen Sea Type Versus Ross Sea Type

The ASP is analogous to the Ross Sea polynya in many biogeochemical aspects. For example, there is high biological productivity in the polynyas but only a small fraction of the produced POC reaches middepths [Dunbar *et al.*, 1998; Smith and Dunbar, 1998; Asper and Smith, 1999; Collier *et al.*, 2000]. Therefore, organic carbon is not efficiently sequestered in the underlying sediments [Sweeney, 2003]. In the Ross Sea, however, the absorbed  $\text{CO}_2$  is subsequently entrained into the bottom water formation and thereby removed from gas exchange for a few centuries [Arrigo *et al.*, 2008b].

## 5. Summary and Conclusions

During the summer field experiments in the ASP, high PP values were observed. However, sinking POC flux to about 400 m and organic carbon accumulation rate in the underlying sediments were lower than a few percent of the various PP estimates, implying that the majority of the sinking POC is converted to fine particles or dissolved forms in the water column. Therefore, carbon sequestration for long-term storage should be dependent on the water circulation pattern on the shelf and in the vicinity. Unlike the Ross Sea and the Weddell Sea, where the Antarctic Bottom Water forms, Circumpolar Deep Water intrudes deep into the Amundsen shelf along the bottom, and the carbon-laden water flows off the shelf in the upper layer. The lack of bottom water formation in the Amundsen Sea reduces the sequestration efficiency of the biological pump system.

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### References

- Arrigo, K. R., and G. L. van Dijken (2003), Phytoplankton dynamics within 37 Antarctic coastal polynya systems, *J. Geophys. Res.*, *108*(C8), 3271, doi:10.1029/2002JC001739.
- Arrigo, K. R., D. Worthen, A. Schnell, and M. P. Lizotte (1998), Primary production in Southern Ocean waters, *J. Geophys. Res.*, *103*, 15587–15600.
- Arrigo, K. R., G. L. van Dijken, and S. Bushinsky (2008a), Primary production in the Southern Ocean, 1997–2006, *J. Geophys. Res.*, *113*, C08004, doi:10.1029/2007JC004551.
- Arrigo, K. R., G. L. van Dijken, and M. Long (2008b), Coastal Southern Ocean: A strong anthropogenic CO<sub>2</sub> sink, *Geophys. Res. Lett.*, *35*, L21602, doi:10.1029/2008GL035624.
- Arrigo, K. R., K. E. Lowry, and G. L. van Dijken (2012), Annual changes in sea ice and phytoplankton in polynyas of the Amundsen Sea, Antarctica, *Deep Sea Res., Part II*, *71–76*, 5–15.
- Asper, V. L., and W. O. Smith (1999), Particle fluxes during austral spring and summer in the southern Ross Sea, Antarctica, *J. Geophys. Res.*, *104*, 5345–5359.
- Behrenfeld, M. J., and P. G. Falkowski (1997), Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnol. Oceanogr.*, *42*, 1–20.
- Bercovici, S. K., B. A. Huber, H. B. DeJong, R. B. Dunbar, and D. A. Hansell (2017), Dissolved organic carbon in the Ross Sea: Deep enrichment and export, *Limnol. Oceanogr.*, doi:10.1002/lno.10592, in press.
- Buesseler, K. O., M. P. McDonnell, O. M. E. Schofield, D. K. Steinberg, and H. W. Ducklow (2010), High particle export over the continental shelf of the west Antarctic Peninsula, *Geophys. Res. Lett.*, *37*, L22606, doi:10.1029/2010GL045448.
- Carlson, C. A., N. R. Bates, H. W. Ducklow, and D. A. Hansell (1999), Estimation of bacterial respiration and growth efficiency in the Ross Sea, Antarctica, *Aquat. Microb. Ecol.*, *19*, 29–244.
- Collier, R., J. Dymond, S. Honjo, S. J. Manganini, R. Francois, and R. Dunbar (2000), The vertical flux of biogenic and lithogenic material in the Ross Sea: Moored sediment trap observations 1996–1998, *Deep Sea Res., Part II*, *47*, 3491–3520.
- DeJong, H. B., R. B. Dunbar, D. A. Koweeck, D. A. Mucciarone, S. K. Bercovici, and D. A. Hansell (2017), Net community production and carbon export during the late summer in the Amundsen Sea, Antarctica, *Global Biogeochem. Cycles*, *31*, 473–491, doi:10.1029/2007JC004551.
- Ducklow, H. W., S. E. Wilson, A. F. Post, S. E. Stammerjohn, M. Erickson, S. Lee, K. E. Lowry, R. M. Sherrell, and P. L. Yager (2015), Particle flux on the continental shelf in the Amundsen Sea Polynya and Western Antarctic Peninsula, *Elementa*, *3*.
- Dunbar, R. B., A. R. Leverter, and D. A. Mucciarone (1998), Water column sediment fluxes in the Ross Sea, Antarctica: Atmospheric and sea ice forcing, *J. Geophys. Res.*, *103*, 30741–30759.
- Ha, H. K., A. K. Wahlin, T. W. Kim, S. H. Lee, J. H. Lee, H. J. Lee, C. S. Hong, L. Arneborg, G. Bjork, and O. Kalen (2014), Circulation and modification of warm deep water on the central Amundsen Shelf, *J. Phys. Oceanogr.*, *44*, 1493–1501.
- Hahm, D., T. S. Rhee, H.-C. Kim, J. Park, Y.-N. Kim, H. C. Shin, and S. Lee (2014), Spatial and temporal variation of net community production and its regulating factors in the Amundsen Sea, Antarctica, *J. Geophys. Res. Oceans*, *119*, 2815–2826, doi:10.1002/2013JC009762.
- Hyun, J.-H., S.-H. Kim, E. J. Yang, A. Choi, and S. H. Lee (2016), Biomass, production, and control of heterotrophic bacterioplankton during a late phytoplankton bloom in the Amundsen Sea Polynya, Antarctica, *Deep Sea Res., Part II*, *123*, 102–112.
- Jacobs, S. S. (1991), On the nature and significance of the Antarctic Slope Front, *Mar. Chem.*, *35*, 9–24.
- Jenkins, A., P. Dutrieux, S. Jacobs, E. J. Steig, G. H. Gudmundsson, J. Smith, and K. J. Heywood (2016), Decadal ocean forcing and Antarctic ice sheet response: Lessons from the Amundsen Sea, *Oceanography*, *29*, 106–117, doi:10.5670/oceanog.2016.103.
- Kim, B. K., H. T. Joo, H. J. Song, E. J. Yang, S. Lee, D. Hahm, T. S. Rhee, and S. H. Lee (2015), Large seasonal variation in phytoplankton production in the Amundsen Sea, *Polar Biol.*, *38*, 319–331.
- Kim, M., J. Hwang, S. H. Lee, H. J. Kim, D. Kim, E. J. Yang, and S. Lee (2016), Sedimentation of particulate organic carbon on the Amundsen Shelf, Antarctica, *Deep Sea Res., Part II*, *123*, 135–144.
- Kim, M., J. Hwang, H. J. Kim, D. Kim, E. J. Yang, H. W. Ducklow, H. S. La, S. H. Lee, J. Park, and S. Lee (2015), Sinking particle flux in the sea ice zone of the Amundsen Shelf, Antarctica, *Deep Sea Res., Part I*, *101*, 110–117.
- Kim, S.-H., A. Choi, E. J. Yang, S. Lee, and J.-H. Hyun (2016), Low benthic respiration and nutrient flux at the highly productive Amundsen Sea Polynya, Antarctica, *Deep Sea Res., Part II*, *123*, 92–101.
- Kim, T. W., H. K. Ha, A. K. Wahlin, S. H. Lee, C. S. Kim, J. H. Lee, and Y. K. Cho (2017), Is Ekman pumping responsible for the seasonal variation of warm circumpolar deep water in the Amundsen Sea?, *Cont. Shelf Res.*, *132*, 38–48.
- Lee, S. H., B. K. Kim, M. S. Yun, H. Joo, E. J. Yang, Y. N. Kim, H. C. Shin, and S. Lee (2012), Spatial distribution of phytoplankton productivity in the Amundsen Sea, Antarctica, *Polar Biol.*, doi:10.1007/s00300-012-1220-5.
- Lee, Y., E. J. Yang, J. Park, J. Jung, T. W. Kim, and S. Lee (2016), Physical-biological coupling in the Amundsen Sea, Antarctica: Influence of physical factors on phytoplankton community structure and biomass, *Deep Sea Res., Part I*, *117*, 51–60.
- Meredith, M. P., H. W. Ducklow, O. Schofield, A. Wahlin, N. Louise, and S. Lee (2016), The interdisciplinary marine system of the Amundsen Sea, Southern Ocean: Recent advances and the need for sustained observations, *Deep Sea Res., Part II*, *123*, 1–6.
- Mu, L., S. E. Stammerjohn, K. E. Lowry, and P. L. Yager (2014), Spatial variability of surface pCO<sub>2</sub> and air-sea CO<sub>2</sub> flux in the Amundsen Sea Polynya, Antarctica, *Elem. Sci. Anth.*, *2*, 000036.

- Nakayama, Y., R. Timmermann, C. B. Rodehacke, M. Schröder, and H. H. Hellmer (2014), Modeling the spreading of glacial meltwater from the Amundsen and Bellingshausen Seas, *Geophys. Res. Letters*, *41*, 7942–7949, doi:10.1002/2014GL061600.
- Ohshima, K. I., et al. (2013), Antarctic bottom water production by intense sea-ice formation in the Cape Darnley polynya, *Nat. Geosci.*, *6*, 235–240.
- Petty, A. A., D. L. Feltham, and P. R. Holland (2013), Impact of atmospheric forcing on Antarctic continental shelf water masses, *J. Phys. Oceanogr.*, *43*, 920–940.
- Pritchard, H. D., S. R. M. Ligtenberg, H. A. Fricker, D. G. Vaughan, M. R. van den Broeke, and L. Padman (2012), Antarctic ice-sheet loss driven by basal melting of ice shelves, *Nature*, *484*, 502–505.
- Reigstad, M., and P. Wassmann (2007), Does *Phaeocystis* spp. contribute significantly to vertical export of organic carbon?, *Biogeochemistry*, *83*, 217–234.
- Smith, W. O., and R. B. Dunbar (1998), The relationship between new production and vertical flux on the Ross Sea continental shelf, *J. Mar. Systems*, *1998*, 445–457.
- Sweeney, C. (2003), The annual cycle of surface CO<sub>2</sub> and O<sub>2</sub> in the Ross Sea: A model for gas exchange on the continental shelves of Antarctica, in *Biogeochemistry of the Ross Sea*, edited by G. R. DiTullio and R. B. Dunbar, *Antarct. Res. Ser.*, *78*, 295–312.
- Thomas, H., Y. Bozec, K. Elkalay, and H. J. W. de Baar (2004), Enhanced open ocean storage of CO<sub>2</sub> from shelf sea pumping, *Science*, *304*, 1005–1008.
- Tsunogai, S., S. Watanabe, and T. Sato (1999), Is there a “continental shelf pump” for the absorption of atmospheric CO<sub>2</sub>?, *Tellus*, *51B*, 701–712.
- Wahlin, A. K., X. Yuan, G. Bjork, and C. Nohr (2010), Inflow of warm circumpolar deep water in the central Amundsen shelf, *J. Phys. Oceanogr.*, *40*, 1427–1434.
- Wahlin, A. K., R. D. Muench, L. Arneborg, G. Bjork, H. K. Ha, S. H. Lee, and H. Alsen (2012), Some implications of Ekman layer dynamics for cross-shelf exchange in the Amundsen Sea, *J. Phys. Oceanogr.*, *42*, 1461–1474.
- Wahlin, A. K., O. Kalen, and K. M. Assmann (2016), Subinertial oscillations on the Amundsen Sea Shelf, Antarctica, *J. Phys. Oceanogr.*, *46*, 2573–2582.
- Weston, K., T. D. Jickells, D. S. Carson, A. Clarke, M. P. Meredith, M. A. Brandon, M. I. Wallace, S. J. Ussher, and K. R. Hendry (2013), Primary production export flux in Marguerite Bay (Antarctic Peninsula): Linking upper water-column production to sediment trap flux, *Deep Sea Res., Part I*, *75*, 52–66.
- Williams, C. M., A. M. Dupont, J. Loevenich, A. F. Post, J. Dinasquet, and P. L. Yager (2016), Pelagic microbial heterotrophy in response to a highly productive bloom of *Phaeocystis antarctica* in the Amundsen Sea Polynya, Antarctica, *Elementa*, *4*.
- Yager, P. L., D. W. R. Wallace, K. M. Johnson, W. O. Smith, P. J. Minnett, and J. W. Deming (1995), The northeast water polynya as an atmospheric CO<sub>2</sub> sink: A seasonal rectification hypothesis, *J. Geophys. Res.*, *100*, 4389–4398.
- Yager, P. L., et al. (2012), ASPIRE: The Amundsen Sea Polynya International Research Expedition, *Oceanography*, *25*, 40–53.
- Yager, P. L., et al. (2016), A carbon budget for the Amundsen Sea Polynya, Antarctica: Estimating net community production and export in a highly productive polar ecosystem, *Elementa*, *4*, 1–36, doi:10.12952/journal.Elementa.000140.