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ASPIRE

The Amundsen Sea Polynya International Research Expedition

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The bridge of RVIB *Nathaniel B. Palmer* looking out upon the Amundsen Sea during early morning hours of December 21, 2010.
Photo by K. Esswein

ABSTRACT. In search of an explanation for some of the greenest waters ever seen in coastal Antarctica and their possible link to some of the fastest melting glaciers and declining summer sea ice, the Amundsen Sea Polynya International Research Expedition (ASPIRE) challenged the capabilities of the US Antarctic Program and RVIB *Nathaniel B. Palmer* during Austral summer 2010–2011. We were well rewarded by both an extraordinary research platform and a truly remarkable oceanic setting. Here we provide further insights into the key questions that motivated our sampling approach during ASPIRE and present some preliminary findings, while highlighting the value of the *Palmer* for accomplishing complex, multifaceted oceanographic research in such a challenging environment.

INTRODUCTION

High-latitude oceans are critical to global elemental cycles, as they are regions of high biological productivity, extensive air-sea heat and gas exchange, and global deepwater formation. The high productivity makes these regions disproportionately important, relative to their size, for the biogeochemical cycling of elements (Sarmiento and Toggweiler, 1984;

Sarmiento et al., 2004). The efficiency of the biological pump in high-latitude seas strongly influences the degree to which carbon is sequestered in the deep sea, and therefore helps drive long-term atmospheric CO₂ concentration (Sigman and Boyle, 2000).

Polynyas, recurring areas of seasonally open water surrounded by sea ice (Figures 1 and 2), are foci for energy and

material transfer between the atmosphere and the polar ocean (Smith and Barber, 2007). Polynyas often dominate the critical exchanges of their regions because the lack of ice in otherwise ice-covered seas allows for dramatic heat and air-sea gas exchange, greater light penetration, and air-sea access for birds and marine mammals. In these seasonally ice-covered areas, springtime conditions create temporally restricted but immense blooms (Smith and Comiso, 2008), with large associated reductions in surface ocean partial pressure of CO₂ ($p\text{CO}_2$; Yager et al., 1995; Takahashi et al., 2002; Sweeney, 2003) and intense sedimentation events (Ducklow et al., 2008).

With high levels of unused macronutrients year-round, the availability of iron (Fe) or light, or both, is thought to limit primary productivity in the coastal

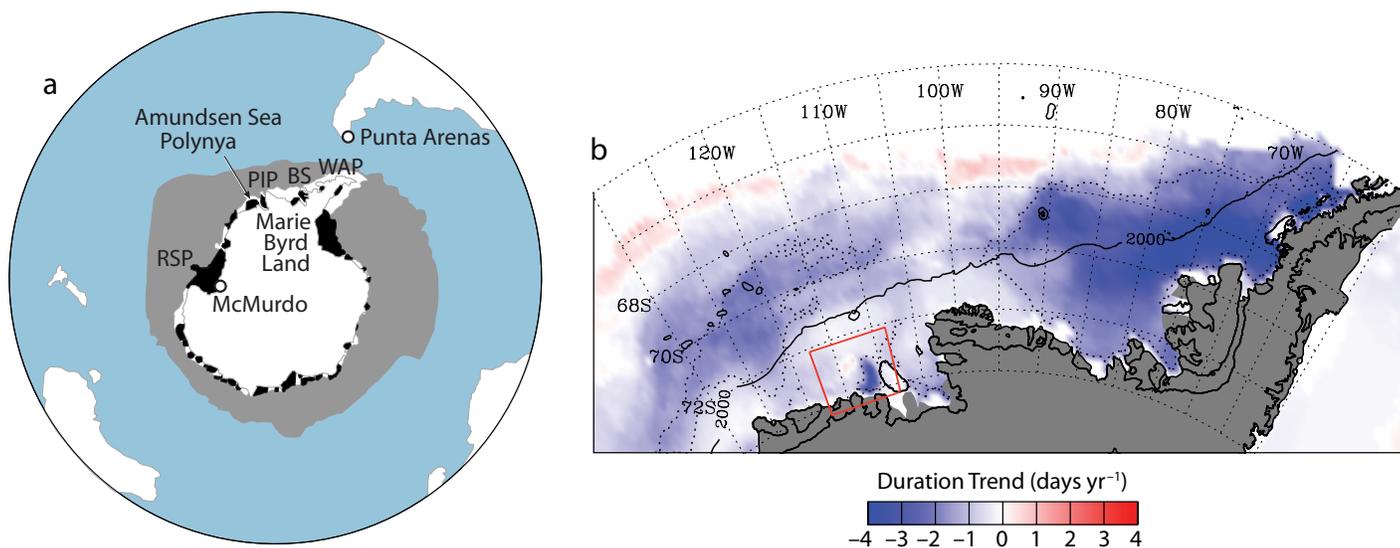


Figure 1. (a) In the southeastern Pacific sector of the Southern Ocean, the Amundsen Sea Polynya is about as far away as you can get from human civilization. This polar stereographic projection shows polynyas in black, typical wintertime sea ice coverage in dark gray, and ice-covered continents and Antarctic continental shelf areas not associated with a polynya in white, with the Ross Sea Polynya (RSP), the Pine Island Polynya (PIP), the Bellingshausen Sea (BS), and the West Antarctic Peninsula (WAP) indicated (modified from Ducklow and Yager, 2007). (b) The 1979/80 to 2010/11 trends (days yr⁻¹) in sea ice season duration for the West Antarctic region of the Southern Ocean, showing strong seasonal decreases in most of the Bellingshausen Sea, over and offshore of the shelf break in the Amundsen Sea, and in the Amundsen Sea Polynya region in front of the Dotson Ice Shelf. The black dotted contour outlines those trends significant at the $p < 0.01$ level, and the black solid contour is the 2,000 m depth line, indicating the shelf break/slope region. The red box outlines the Amundsen Sea Polynya region shown in Figure 2 (modified from Stammerjohn et al., 2012).

Antarctic (Sunda and Huntsman, 1997; Boyd, 2002). Iron is required for the photosynthetic apparatus and electron transport pathways of all phytoplankton, as well as for nitrate assimilation. Iron and light limitation of photosynthesis are linked because the Fe requirement increases at low irradiance (Raven 1990).

Much of the primary production in Antarctic polynyas is carried out by

microscopic algae, either *Phaeocystis antarctica* or diatoms. The relative contributions of these two phytoplankton taxa influence the biogeochemistry and the ecology of the region and may be climate sensitive (e.g., Arrigo et al., 1999; Alderkamp et al., 2012a; Frago and Smith, 2012). For example, *P. antarctica* takes up twice as much CO₂ per mole of phosphate removed than diatoms

(Arrigo et al., 1999), and it is not readily grazed by microzooplankton (Caron et al., 2000).

While not every polynya is inherently productive (Figure 3, inset), primary production per unit area in Antarctic polynyas typically exceeds 1 g C m⁻² d⁻¹ on average, much higher than offshore waters of the open Southern Ocean (0.2–0.4 g C m⁻² d⁻¹;

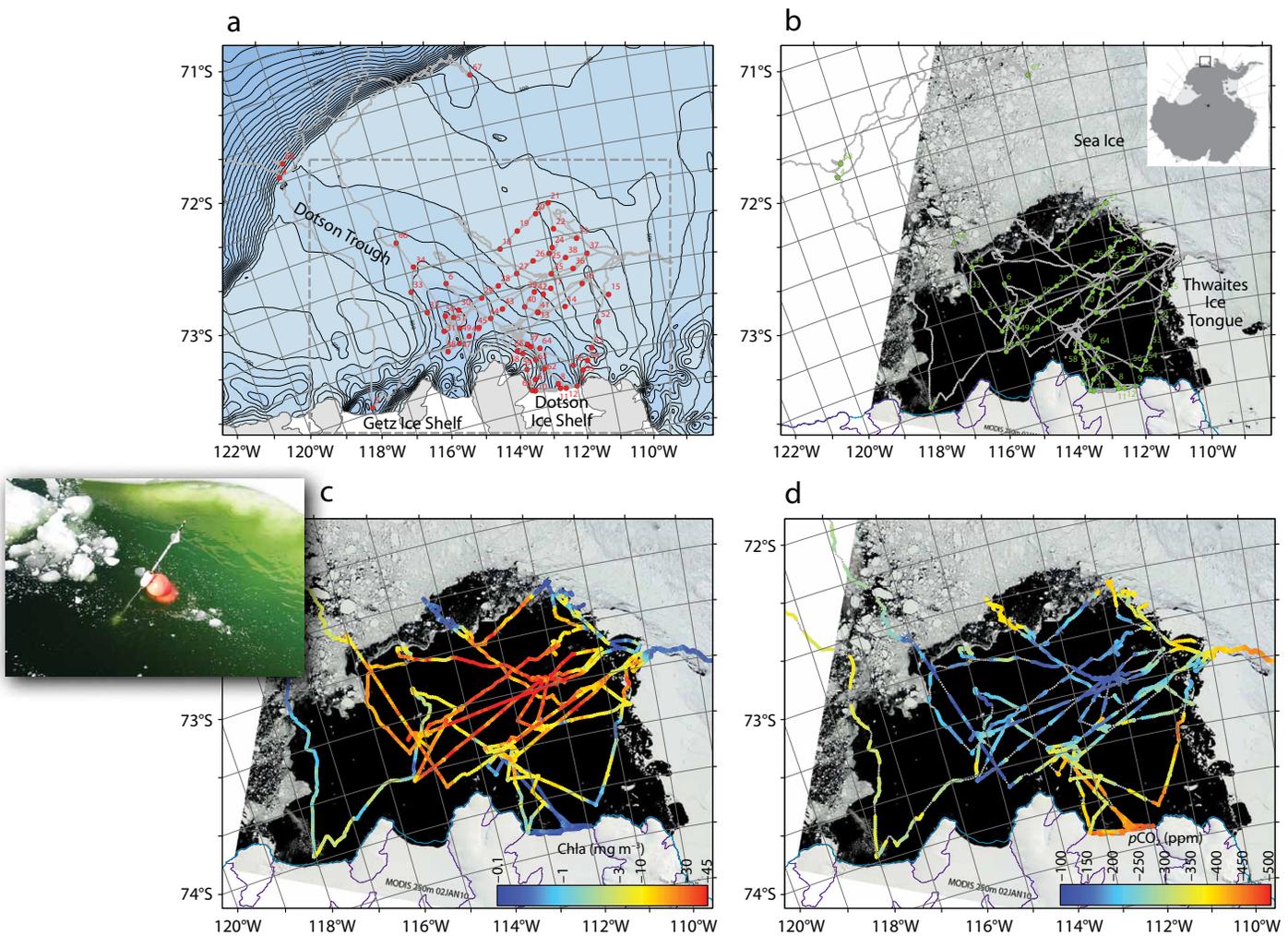


Figure 2. (a) The ASPIRE stations (red numbers) and cruise track (gray line) superimposed on the continental shelf bathymetry (black lines); the dashed boxed depicts the areas shown in (c–d). (b) Moderate Resolution Imaging Spectroradiometer (MODIS) sea ice reflectance satellite image from January 2, 2011, showing polynya extent in relation to station numbers (green) and cruise track (white dashed line). (c) Chlorophyll *a* fluorescence in surface seawater measured continuously from the underway seawater system. Scale bar is nonlinear to emphasize the areas of high concentrations (bloom) in red and orange. Inset photo shows very green water at Station 35 (December 27, 2011; courtesy of D. Munroe). (d) Partial pressure of carbon dioxide in surface seawater (*p*CO₂) measured continuously from the underway seawater system. Atmospheric values are approximately 390 ppm (light orange), so blue/green/yellow values are below atmospheric saturation; orange/red values indicate supersaturation.

Arrigo et al., 2008a). The Amundsen Sea, located off west Antarctica (Figure 1), harbors two particularly productive polynyas, the Amundsen Sea Polynya, ~ 27,000 km², and the Pine Island Polynya, ~ 18,000 km² (Arrigo et al., 2012). Specifically, the Amundsen Sea Polynya is, on average, the most productive polynya (per unit area) in the Antarctic (Figure 3, inset), with the highest interannual variation (Arrigo and van Dijken, 2003). Compared to the much larger and well-studied Ross Sea Polynya, satellite data show that seasonally averaged chlorophyll *a* levels in the Amundsen Sea Polynya ($2.2 \pm 3.0 \text{ mg m}^{-3}$) are more than 40% higher than the Ross Sea Polynya ($1.5 \pm 1.5 \text{ mg m}^{-3}$). Also, the bloom in the Amundsen Sea Polynya peaks later than in the Ross Sea Polynya (January instead of December), and mean chlorophyll *a* concentrations are more variable from year to year (1997–2002)—138% of the mean in the Amundsen Sea Polynya, 101% in the Ross Sea Polynya. This difference is especially meaningful because the Ross Sea Polynya is already considered to be quite variable (Smith et al., 2006).

Glaciologists report that glaciers near the Amundsen Sea Polynya are undergoing some of the fastest rates of acceleration and thinning on the Antarctic Continent (Rignot, 2008). This rapid melting is driven far less by warmer air temperatures than by the increased presence of relatively warm (~ 2°C) Circumpolar Deep Water (CDW) beneath the ice shelf (Jenkins et al., 2010; Jacobs et al., 2011), offering a prime case study for climate-ocean-ice interactions. The rapid glacial thinning threatens to raise global sea level much faster than previously estimated. Moreover, because glacial meltwater also affects ocean

buoyancy, stratification, and trace metal distribution, the regional oceanography and biogeochemistry of the Amundsen Sea are likely affected as well.

The summer sea ice extent in the central Amundsen Sea Polynya region shows some of the strongest recent declines in the Southern Ocean (Figure 1b), comparable to the widely reported decreases in the Bellingshausen Sea (Parkinson and Cavalieri, 2012; Stammerjohn et al., 2012). In the Amundsen Sea Polynya region, the length of the sea ice season has declined by 60 ± 9 days since 1979, a change largely due to the Amundsen Sea Polynya opening earlier in the year by 52 ± 9 days. The shorter sea ice season

facilitates increased solar ocean warming, leading to greater ice declines. The loss is thought to be primarily due to climate-related changes in the winds, specifically a poleward intensification of the prevailing storm tracks in the Amundsen-Bellingshausen Sea region (Marshall, 2007; Stammerjohn et al., 2012).

ASPIRE ON RVIB NATHANIEL B. PALMER

The Amundsen Sea Polynya is an extraordinary place. It takes about two weeks by ship to get to the Amundsen Sea from the nearest port, and an ice-classed ABS A2 icebreaker is required to make it through the heavy sea ice that

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guards the coastal polynyas near the ice shelf (Figures 1 and 2). Few oceanographic expeditions have made it into the Amundsen Sea. The Amundsen Sea Polynya thus offered both a critical challenge to the US Antarctic Program (USAP) research fleet and a unique opportunity for studying an important but poorly understood, climate-sensitive marine system. With extraordinary field support provided by RVIB *Nathaniel B. Palmer*, its officers and crew, along with the technical support of Raytheon Polar Services, an international team of

scientists (the Amundsen Sea Polynya International Research Expedition: ASPIRE) investigated regional oceanography and productivity in the Amundsen Sea Polynya during December 2010 to January 2011. The project was a close collaboration with the Swedish icebreaker *Oden*, which worked primarily in the pack ice to the north, while the ASPIRE program was conducted within and adjacent to the polynya (Figure 2a). Our objective was to investigate why the Amundsen Sea Polynya is so much more productive than other polynyas

and whether spatial and seasonal variability in the region provide insight into climate-sensitive mechanisms driving carbon fluxes.

Onboard the *Palmer*, we sampled the polynya and the adjacent sea ice zone with our primary sampling tools: conventional and trace metal clean conductivity-temperature-depth (CTD)/rosettes, various net tows for zooplankton, in situ pumps for particulate material, a towed camera system for seafloor imaging (Seasled from the Woods Hole Oceanographic Institution), short-term (two- to three-day) floating and long-term (one-year) moored sediment traps for sinking detritus, Smith Mac benthic grab for seafloor sediment samples, smaller ring nets for additional plankton samples, and an autonomous depth-profiling (0–100 m) Webb Slocum glider. We also deployed and recovered long-term physical oceanographic moorings for the Amundsen Sea Embayment Project (e.g., Jacobs et al., 2011), and collected sea ice and snow samples using a crane-assisted basket. The ship's underway system continuously measured surface water properties: temperature, salinity, phytoplankton fluorescence (including Fluorescence Induction and Relaxation, FIRE; Gorbunov and Falkowski, 2005), and oxygen and carbon dioxide concentrations. Between stations, discrete water samples were also collected from the underway system for additional nutrient and plankton analyses. Our shipboard planning and activities, especially our icebreaking efficiency, were greatly assisted by near-daily regional sea ice satellite images collected by the Moderate Resolution Imaging Spectroradiometer (MODIS; e.g., Figure 2b–d), Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), and

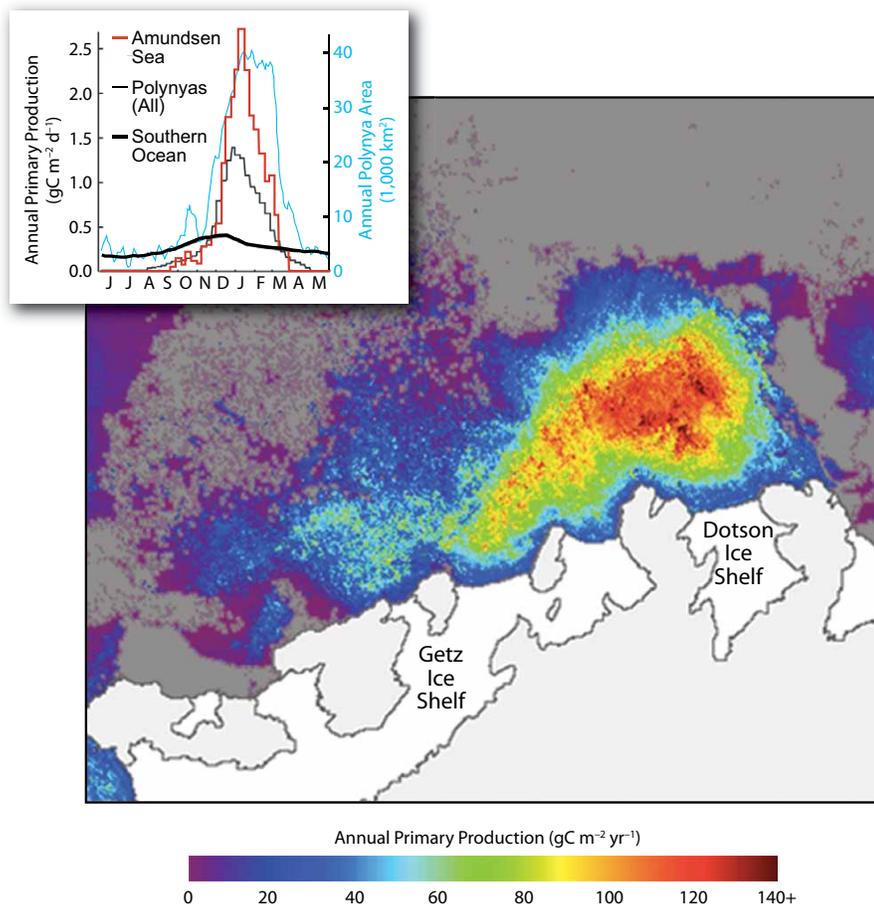


Figure 3. Satellite-based annual primary production in the Amundsen Sea Polynya during the 2010–2011 season. Also shown are waters that remained ice-covered (dark gray) and the continent and ice shelves of Antarctica (light gray and white). Inset shows annual cycle of mean primary production for all Southern Ocean waters south of 50° (heavy black line), the average of 37 Antarctic coastal polynyas (thin black line), and the Amundsen Sea Polynya (red line) (modified from Arrigo and van Dijken, 2003). A comparison with the seasonal change in polynya area (blue) shows how the production drops off well before the ice returns.

Envisat, subsampled for our sampling region and emailed to us on the ship by the Polar Geospatial Center (<http://www.agic.umn.edu>).

ASPIRE occupied a dense array of stations across and along key bathymetric features (Figure 2a), including the deep Dotson Trough bisecting the continental shelf and the shallower plateau to the east. We also sampled close to known sources of glacial and sea ice meltwater (Figure 2b), including the Dotson Ice Shelf to the south, the Thwaites Iceberg Tongue to the east and the pack ice to the north. This high-density sampling in the Amundsen Sea Polynya region will help us compile for the first time a high-resolution, three-dimensional map of physical, biological, and biogeochemical properties, including the presence or absence of meltwater and bioavailable iron. Although many of our sample and data analyses are still underway, here we provide further insights to the key questions that motivated our sampling approach during ASPIRE, and discuss some preliminary findings.

PRODUCTIVITY IN THE AMUNDSEN SEA POLYNYA 2010–2011

During ASPIRE, high near-surface chlorophyll *a* fluorescence was found through much of the polynya (Figure 2c), corroborated by discrete surface chlorophyll *a* measurements exceeding 30 mg m^{-3} . Upon entering the polynya in mid-December, we observed low values ($< 1 \text{ mg m}^{-3}$) along the face of the Dotson Ice Shelf and in the sea ice zone bordering the polynya to the east and north. Intermediate values were observed in mid-December in the western polynya and in front of the Getz Ice Shelf. Highest values ($> 20 \text{ mg m}^{-3}$)

were observed in the central polynya, north of $73^{\circ}40'S$, at stations sampled after December 20. High phytoplankton biomass was associated with low ($< 10 \text{ } \mu\text{mol L}^{-1}$) nitrate concentrations that showed significant nitrate depletion from pre-season surface concentrations of $\sim 31 \text{ } \mu\text{mol L}^{-1}$.

Satellite-based estimates over the open water season (roughly October to March) corroborate high annual productivity in the central polynya in 2010–2011 (Figure 3). Production was lower in the west and along the northern sea ice edges, as these waters became ice-free later in the season and thus had a shorter growing season. Lower production in the south was likely due to a less stable water column. Average daily net primary production (NPP) per unit area for the polynya in 2010–2011 was $0.48 \pm 0.47 \text{ g C m}^{-2} \text{ d}^{-1}$. The maximum daily rate was $2.2 \text{ g C m}^{-2} \text{ d}^{-1}$. The annual NPP per unit area was $88 \text{ g C m}^{-2} \text{ yr}^{-1}$, integrated over a 185-day period. Total annual NPP for the Amundsen Sea Polynya in 2010–2011 was 4.0 Tg C yr^{-1} , about 20% higher than the average for 1997–2010 ($3.3 \pm 1.1 \text{ Tg C yr}^{-1}$; Arrigo et al., 2012).

Qualitative microscopic observations during ASPIRE showed that colonial *P. antarctica* dominated the phytoplankton bloom in the central polynya; diatoms were also present but at lower concentrations. *P. antarctica* also dominates blooms in the Ross Sea Polynya (Arrigo et al., 1999) and Pine Island Polynya (Alderkamp et al., 2012a). In contrast, diatoms dominated marginal ice zones sampled on previous Amundsen Sea expeditions (March and December 2007; Fragoso and Smith, 2012).

The near-surface $p\text{CO}_2$ (Figure 2d; Takahashi et al., 2011), measured

underway, was inversely correlated to near-surface chlorophyll *a* ($r = 0.76$, $n = 6,600$; Mu and Yager, 2012). In the central polynya, $p\text{CO}_2$ was highly undersaturated, as low as 100 ppm, nearly 300 ppm below atmospheric concentrations. Interestingly, it was supersaturated in the region near the Dotson Ice Shelf where upwelling of Modified CDW (MCDW) may be occurring (see below). Estimates of CO_2 uptake by the undersaturated region of the central polynya were $0.28 \text{ g C m}^{-2} \text{ d}^{-1}$, or $2.3 \pm 0.5 \text{ Tg C yr}^{-1}$, when summed over 185 days (Mu and Yager, 2012). This estimate of net community production (NCP) corresponds well with the satellite-based NPP.

Looking below the surface, within the upper 100 m, the Slocum glider provided a high-resolution survey of the upper water column in the central polynya and showed that chlorophyll *a* concentrations were highest in relatively warmer (-0.2 to -1°C) and fresher waters (33.7 – 33.8 ; Figure 4), and that these high concentrations often persisted down to 60 m. These water properties typically reflect the influence of melting sea ice, which stratifies the water column and allows solar radiation to warm the surface waters over time. Thus, warmer waters likely have been ice-free longer. The high phytoplankton biomass in the fresher, warmer waters could also reflect the input of Fe or other micronutrients associated with sea ice or upwelled, glacier-derived meltwater, higher light levels in the shallow upper mixed layer, or a combination of these factors.

Temperature-salinity (T-S) plots for the glider (upper 100 m) and for the full-depth shipboard CTD data taken in the polynya region (Figure 4b,c) indicate three major water masses: (1) Antarctic Surface Water, comprising a range of

seasonally freshened, warmed surface waters; (2) Winter Water, saltier, near-freezing water formed by the previous winter's sea ice production; and (3) MCDW, the warmest and saltiest water found in the Amundsen Sea Polynya region. We also saw glacial meltwater layers at depth (e.g., emanating from the Dotson Ice Shelf and traversing the polynya region). These layers can be qualitatively identified in T-S space in relation to the mixing line between CDW and pure meltwater (the grey dotted line in Figure 4b; Gade, 1979; Wählin

et al., 2010). Typical water masses or features within the Dotson Trough consisted of (from surface to bottom): Antarctic Surface Water, Winter Water, glacial meltwater, MCDW. In contrast, the water column in some of the shallower regions east of the Dotson Trough appeared only to consist of Antarctic Surface Water and Winter Water. The T-S plot with all CTD data shows many of our sampling sites with values near the CDW-meltwater mixing line, indicating the presence of subsurface meltwater. The question we are now exploring

is where and how this meltwater gets entrained into the euphotic zone, as it may be a source of bioavailable iron fueling the intense production.

PRODUCTIVITY AND IRON SOURCES IN THE AMUNDSEN SEA POLYNYA ARE CLIMATE SENSITIVE

High interannual variability in Amundsen Sea Polynya productivity invokes strong climate sensitivity. As measured by satellite, variability in total production in the Amundsen Sea

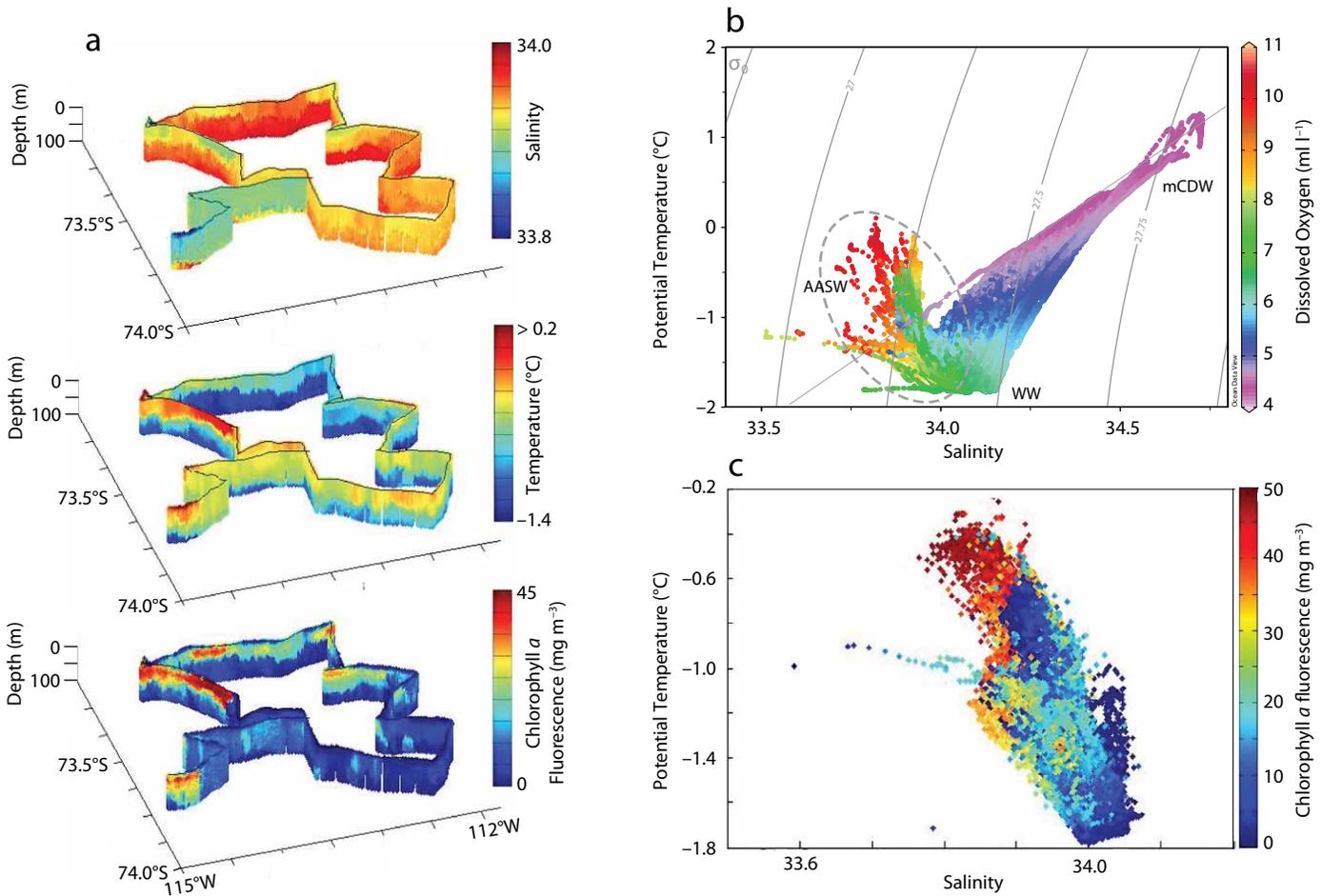


Figure 4. Glider observations greatly expand the ship's sampling footprint. (a) Data collected by the Webb Slocum glider showing three-dimensional ribbon maps of salinity, temperature, and chlorophyll *a* fluorescence, indicating high chlorophyll *a* levels in the north and east regions of the sampling track, coincident with low salinity (< 34), and warmer (> -1°C) waters. (b) Temperature (T)-salinity (S)-oxygen plot of all the CTD data collected in the polynya region with labels identifying key water masses: Antarctic Surface Water = AASW. Winter Water = WW. Modified Circumpolar Deep Water = MCDW. The grey dotted line represents the mixing line between CDW and meltwater, and the grey oval outlines the area in T-S space sampled by the glider. (c) Temperature-salinity-chlorophyll *a* plot for the glider surveys showing high chlorophyll *a* associated with lower salinity (< 34) and warmer (> -1°C) water.

(Arrigo et al., 2012) appears to be linked to the timing of the polynya's opening and its duration. Sea ice distribution almost certainly sets the first-order control on productivity in polynyas via its direct influence on light availability and wind-driven mixing. Because of the possible co-limitation by light and Fe, an important issue is the climatological link between changes in sea ice cover and changes in ocean circulation and stratification. An increase in Fe supply may not translate into an increase in production or export if there is not also a reduction in mixed-layer depth (e.g., Mongin et al., 2007; Krishnamurthy et al., 2008), or vice versa. Reduced mixed-layer depth in spring is related to sea ice melt, which freshens the surface, inducing shallow stratification that subsequently warms by increased insolation. But winds may break down the seasonal stratification and deepen the mixed layer. Changes in the timing of sea ice retreat affect the timing and magnitude of the initial bloom period. As described above, there has been a strong trend toward an earlier spring sea ice retreat in the Amundsen Sea Polynya region, which may enhance bloom magnitude (Arrigo et al., 2012), but how such changes might affect trophic interactions and carbon export are areas of active research (e.g., Ducklow et al., 2012).

The timing and duration of the intense phytoplankton bloom in the Amundsen Sea Polynya also suggests that bioavailable Fe must be supplied continuously throughout the summer, consistent with recent findings for the Ross Sea (Sedwick et al., 2011) and Pine Island Polynyas (Gerringa et al., 2012). While melting sea ice may supply Fe to the polynya edges, it is unlikely that this supply can provide sufficient Fe to

maintain the central polynya bloom for its entire summer duration. Instead, Fe may be resupplied by periodic or local vertical mixing of a deeper Fe pool, driven by winds or eddies, or by lateral mixing from coastal sources within the upper mixed layer. Thus, the key questions addressed by our trace metal sampling program were: What are the sources and pathways of bioavailable Fe inputs and how are they delivered to the euphotic zone? Do we see a substantial pool of dissolved Fe within or just below the mixed layer? Does dissolved Fe in the euphotic zone increase in proximity to the continent? Figure 5 summarizes the hypothesized potential pathways for the delivery of Fe to the polynya, based in part on early ASPIRE results. Although not all of these mechanisms are discussed in the following, this schematic diagram provides a summary of the pathways being investigated through the developing ASPIRE data set.

The increases in MCDW on the continental shelf (Thoma et al., 2008), and the associated melting of ice shelves and marine glaciers (Shepherd et al., 2004; Martinson et al., 2008; Jacobs et al., 2011) may supply a substantial flux of bioavailable iron (Hiscock et al., 2003; Helene Planquette, National Oceanographic Centre, *pers. comm.*, May 30, 2012) as well as affect water column stability in the polynya. ASPIRE observations confirmed the presence of MCDW at depth (first identified aboard the *Palmer* in 1994; Hellmer et al. 1998; with subsequent measurements in 2000, 2007, and 2009; Wählin et al., 2010; Jacobs et al., 2011). CDW gains access to the continental shelf at the shelf break, particularly at seafloor depressions, and ponds in glacially scoured troughs that extend deep beneath the

ice shelves. It may preferentially enter the eastern Amundsen Sea at depth (Walker et al., 2007; Thoma et al., 2008) with little temperature/salinity modification (Jacobs et al., 2011); hence, the Amundsen Sea could represent an end member among Antarctic margin systems influenced by Antarctic Circumpolar Current-regulated inputs.

The glacial source of iron is hypothesized to result from the partial dissolution of minerals embedded in basal ice (Raiswell and Canfield, 2012), and also from the reaction of terrestrial Fe particles with seawater as they are released to suspension by ~ 2°C MCDW circulating under the major ice shelves (Crossen, Dotson, and Getz) along the southern polynya border, adding meltwater and increasing buoyancy and vertical mixing. Recent work on circulation under the Pine Island Glacier (Jenkins et al., 2010; Jacobs et al., 2011) suggests that water emerges with substantial concentrations of suspended particles and may have high dissolved Fe concentrations as a result of basal melting and/or sediment resuspension (near the grounding line; Gerringa et al., 2012). Productivity in the adjacent Pine Island Polynya appears to be fertilized by this input (Alderkamp et al., 2012a). Analysis of ASPIRE samples collected adjacent to the Dotson Ice Shelf suggest that outflow from under this major ice shelf has a detectable meltwater fraction (Randall-Goodwin, 2012) and is indeed enriched in dissolved and particulate Fe, from 600 m depth all the way up to the subeuphotic zone at 80 m. These relatively buoyant waters can be traced throughout the Dotson Trough region and may mix further into the euphotic zone as they spread north and interact with water masses in the central polynya. This possibility raises additional

questions for the ASPIRE team: Can we trace meltwater layer(s) emanating from the Dotson Ice Shelf? If meltwater is present at depth, how does it then become available to the euphotic zone?

If ice shelves are important Fe sources, then icebergs resulting from ice shelf calving may also play a role in supplying

Fe to the surface ocean (Lin et al., 2011). ASPIRE was able to sample close to a free-drifting iceberg. Our preliminary findings suggest that this iceberg was acting to stimulate vigorous vertical mixing (Randall-Goodwin, 2012), consistent with recent studies near a Weddell Sea iceberg (Stephenson et al.,

2011), and that this physical mechanism, spawned by drifting icebergs, may mix subsurface inventories of dissolved Fe into the euphotic zone, supplementing or exceeding Fe inputs from the melting iceberg itself.

The quantification of these sources and pathways of Fe delivery will be

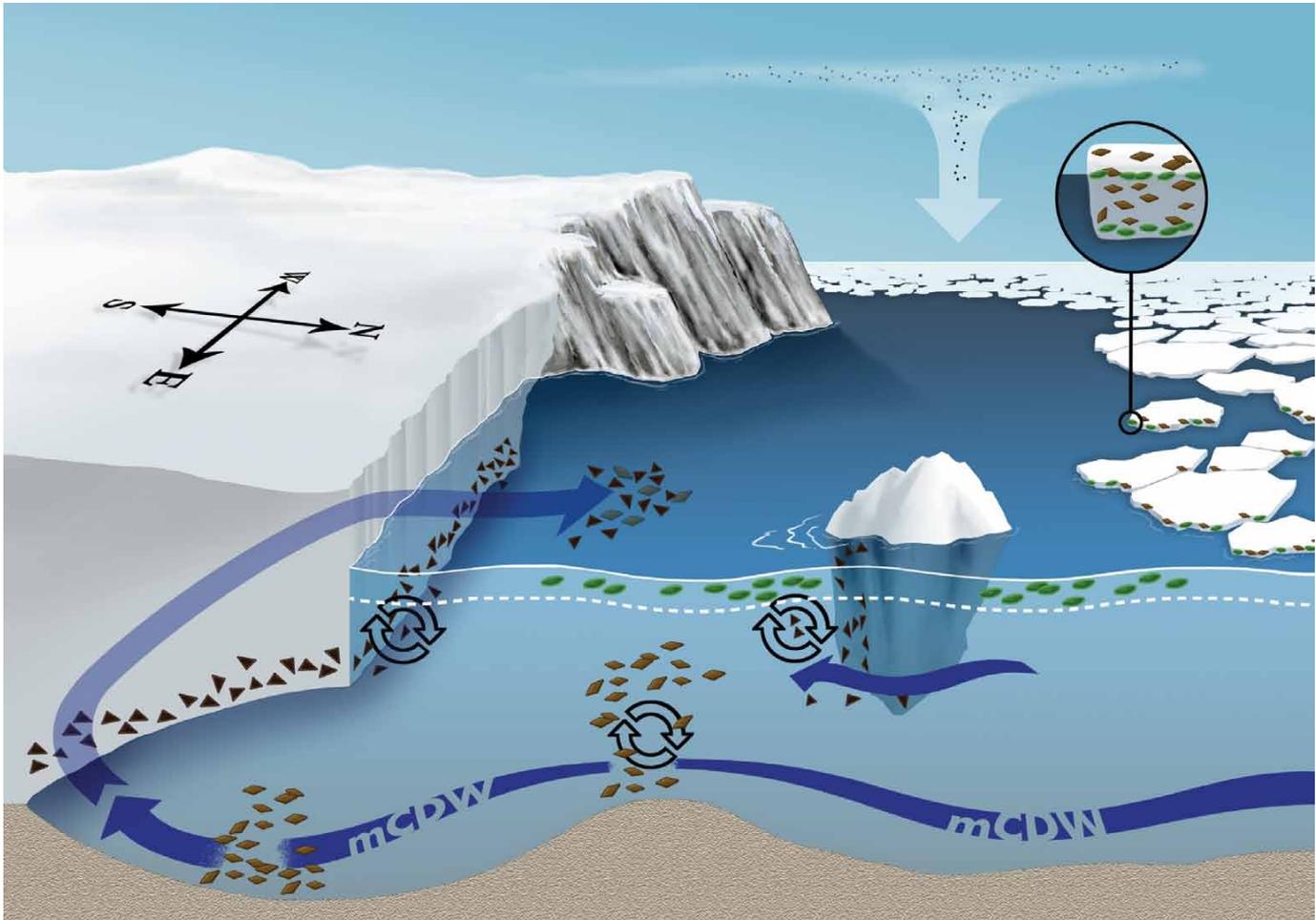


Figure 5. Cutaway diagram of the Amundsen Sea Polynya showing processes thought to contribute dissolved and particulate Fe to the polynya water column. The Dotson Ice Shelf is depicted forming part of the southern polynya boundary, sea ice is on all other sides, and an iceberg is drifting north through the open water, as observed during ASPIRE. Phytoplankton (green ovals) are growing dominantly in the central polynya, within the euphotic zone (lower boundary is dotted line). Modified Circumpolar Deepwater (MCDW) flows south from the shelf break and receives Fe from sedimentary sources (golden rectangles) as it interacts with the seafloor both on the open continental shelf and as it flows under the ice shelf. Resuspended sedimentary Fe may also be mixed up into the water column in the open polynya, where wind events may bring it into contact with the euphotic zone. As the ~1–2°C MCDW flows under the ice shelf, basal ice is melted and the long-entombed mineral particles (black triangles) are released, joining the resuspended material, and injected into the polynya as MCDW exits the ice shelf near the western end. This outflow is made more buoyant by the fresh meltwater addition, and it rises as it flows north, helping to mix dissolved and particulate Fe of glacial origin into the upper water column. The wind-blown iceberg is also melting as it traverses the polynya, and may have basal Fe minerals on its bottom or lateral faces, depending on whether it has rotated from its original vertical position. Just as importantly, the moving iceberg generates powerful vertical mixing in its wake eddies, helping to mix subsurface Fe into the euphotic zone. Sea ice contains both Fe mineral particles that were stripped from the water column during its formation, and Fe-rich phytoplankton cells, both of which are released to surface waters when the sea ice melts. ASPIRE investigated each of these processes and is working to understand their relative importance in supplying the Fe that fuels the intense season-long productivity in the polynya.

inferred from ASPIRE data using three-dimensional maps of both dissolved and particulate Fe distributions, interpreted within the context of physical hydrography, current measurements, and biological productivity. Measurements of additional bioactive metals (dissolved Mn, Zn, Cu, Ni, and Co, as well as these and other elements in suspended particles), and of neodymium isotope ratios, are helping us track the processes that supply and remove Fe. Analyses of particles collected during drifting sediment trap deployments in the central polynya will provide estimates of the composition and flux of particles removing Fe from the euphotic zone. ASPIRE will produce a comprehensive and quantitative assessment of the dynamics of Fe and related bioactive metals in this highly productive and important Antarctic shelf system.

To determine how light and Fe availability constrain productivity in the Amundsen Sea Polynya, and to explore the interactions between these two variables, bioassay experiments were performed during ASPIRE in which Fe was added to phytoplankton assemblages collected at several stations, the assemblages were incubated under various light conditions, and they were then compared to control treatments without Fe addition. The incubations were monitored for changes in phytoplankton photophysiology, productivity, and microheterotrophic activity. Preliminary results suggest that Fe addition stimulated phytoplankton growth and photosynthesis rates at some, but not all, stations in the polynya, indicating regionally diverse Fe nutritional status of the phytoplankton assemblages (Alderkamp et al., 2012b). This differentiates the Amundsen Sea Polynya from the Pine Island Polynya, where Fe

additions did not affect phytoplankton growth during the phytoplankton bloom in 2008–2009 (Mills et al., 2012). The ensuing task is to relate these spatial patterns to the availability of dissolved and particulate Fe, and to variations in light and in mixing environments.

THE FATE OF PRODUCTIVITY IN THE AMUNDSEN SEA POLYNYA

Climate-driven variability in primary production is only part of the story. A key conceptual framework in biological oceanography is the idea that the structure of planktonic communities profoundly affects export and sequestration of organic material (the biological carbon pump) and the chemical cycling of nutrients (Michaels and Silver 1988; Legendre and Le Fevre 1995; Ducklow et al., 2001b). Thus, ASPIRE was also interested in how climate may affect zooplankton community structure (Smetacek et al., 2004; Murphy et al., 2007), bacterial activity and community structure (Ducklow and Yager, 2007), the efficiency of organic matter export (Smith and Dunbar, 1998; Arrigo et al., 1999), and CO₂ uptake by the coastal Antarctic (Arrigo et al., 2008b). Ultimately, we hope to understand how climate affects overall carbon sequestration by the Amundsen Sea Polynya, and how this sequestration may serve as a feedback to increasing atmospheric CO₂ concentrations. Once all the data are in, a full carbon budget exercise is planned to better determine the microbial fate of carbon in the polynya.

Whether a polynya ecosystem is carbon “retentive” (*sensu* Wassmann, 1998) or exports carbon to depth can vary seasonally or interannually and is sensitive to local forcing. Unfortunately, the mechanisms, which are related to

bloom magnitude and community structure (Karl, 1993), are poorly understood (Boyd and Trull, 2007). Zooplankton consume phytoplankton and particulate material and convert them partially into rapidly sinking fecal pellets as well as some dissolved material. The degree to which sinking particles are remineralized depends on the activities of microorganisms responsible for enzymatically converting the organic matter to a dissolved form that can be incorporated and then respired (Azam and Long, 2001; Simon et al., 2002). Bacteria in polynyas are known to play important roles in regulating carbon and nutrient fluxes and to respond dynamically to the changes in environmental conditions associated with seasonal variation (reviewed by Ducklow and Yager, 2007). Top-down pressures on bacteria (e.g., viruses or bacteriovores) may shunt material from the sinking to the dissolved pool, leading to lower export (Fuhrman, 1992), or it may simply limit bacterial remineralization, enhancing export.

These processes were all observed by ASPIRE; overall, preliminary indications are that the Amundsen Sea Polynya is a fairly efficient export system. Estimates of air-sea gas exchange (similar to NCP) are about 60% of independent estimates of NPP, suggesting high export efficiency. ASPIRE observations support sinking of phytoplankton to depths below the euphotic zone and ultimately to the sediment: we found high chlorophyll *a* containing material (“green” particles) on filters collected from the in situ pumps deployed below the euphotic zone, there was an abundance of bright green material in the short term (two to three day) floating sediment traps (60 m, 150 m, and 300 m), and greenish sediments were collected by the Smith Mac

benthic grab. Imaging of the seafloor using a towed camera system (Seasled) near the southeastern Dotson Trough (73.6–73.7°S, 112–113°W) provided no visual evidence for deposition of phyto-detritus. However, satellite ocean color images of that area also suggest that a bloom had not yet developed there at the time of observations (December 18).

Paraeuchaeta antarctica, the amphipod *Orchomene* spp., and several species of gelatinous zooplankton. Other krill species were observed in very low abundances. Nearly all of the krill species were in juvenile or larval forms. We also found that the zooplankton community structure in the polynya differed significantly from that observed near the

Preliminary results (Williams et al., 2012) from measurements of bacterial growth, respiration, exoenzyme activities, and substrate utilization indicate a psychrophilic (cold-loving), often particle-associated, bacterial community that was actively growing and respiring at rates comparable to or in excess of rates previously measured during peak bloom periods in the Ross Sea (Ducklow et al., 2001a). Depth integrated bacterial production ranged from 0.2–2.8 mg C m⁻² d⁻¹, with maximum volumetric rates (0.2–4 µg C L⁻¹ d⁻¹) near the surface. Near-surface respiration rates were typically 10–20 times higher than growth rates, so gross growth efficiencies averaged 6 ± 3%, with the highest efficiency (16%) corresponding to the highest bacterial productivity.

Our estimate of bacterial carbon demand (3–67 mg C m⁻² d⁻¹) seems fairly low (< 15%) relative to the substantial rates of primary production (reported above), but it is consistent with observations of an efficient biological pump. Typically, about 40% of the organic matter produced in marine waters is channelled through heterotrophic bacteria living in the water column (Duarte and Cébrian, 1996). We did observe very high rates of bacterial activity on material collected by floating sediment traps, indicating that particles are remineralized as they sink.

Ongoing work aims to link variability in activity to variation in the composition of the microbiome. Next-generation sequencing-enabled analyses of 16S rRNA gene assemblages documented highly diverse communities of bacterioplankton, where the composition was strongly coupled to discrete water masses and also influenced by productivity and other water characteristics. We hypothesize that the significance and

“...ASPIRE IS MOVING US FORWARD IN OUR UNDERSTANDING OF ECOSYSTEM CHANGE IN AN IMPORTANT POLYNYA SYSTEM.”

ZOOPLANKTON

In contrast to the high phytoplankton biomass described above, observations from zooplankton net tows suggest a surprisingly low overall zooplankton biovolume at all depths (maximum was 0.5 mL m⁻³; but typically < 0.1 mL m⁻³) with a subsurface maximum typically between 60 m and 150 m. The most abundant of the large zooplankton species were the euphausiid *Euphausia crystallarophias* and the calanoid copepod *Paraeuchaeta antarctica*. Very few zooplankton were observed in the upper 60 m for most of the stations with the exception of *E. crystallarophias*, which tended to stay within the upper 150 m. *Calanoides acutus* and *Metridia gerlachi* were important below 60 m. The upper water column samples were dark green because of very high *Phaeocystis* cell densities. This observation might confirm earlier studies that *Phaeocystis* is not readily grazed by zooplankton. The deeper nets collected

shelf break in the pack ice (Station 68; Figure 2a). Preliminary data therefore suggest that the polynya zooplankton community was still developing, and that significant zooplankton impact on the surface bloom likely occurs later in the season.

MICROORGANISMS

Data from stations throughout the Amundsen Sea Polynya revealed a large spatial heterogeneity of microbial biomass. Flow-cytometric enumeration of bacteria, viruses, and protozoa showed a distribution corresponding to the abundance of primary producers and their activity, and decreasing abundance with depth. Bacterial abundance varied from 1.2–7.5 × 10⁸ cells L⁻¹ within the studied region, whereas the corresponding range for viruses was 1.6–8.2 × 10⁹ viruses L⁻¹. These numbers are similar to earlier estimates from other productive regions of the Southern Ocean (Granéli et al., 2004).

balance of key microbial processes are intimately linked to community composition (Bertilsson et al., 2007) and that a mechanistic understanding of how microbial communities are organized will help us understand constraints and controls in the polynya, as well as their biogeochemical significance.

POLAR REGIONS ARE CHANGING RAPIDLY

What does the future hold for the Amundsen Sea Polynya? Overall, the observed reduction in summer sea ice extent (1979–2010 trend; Parkinson and Cavalieri, 2012) and the length of the sea ice season (Stammerjohn et al., 2012) are likely to continue or perhaps accelerate in the near term. Similarly, thinning rates of nearby glaciers are accelerating (Rignot, 2008), and thus glacial melt-water effects on physical, biological, and biogeochemical properties of the polynya will increase in the near future.

Overall, warming will result in stratification and melting of both sea ice and ice shelves, and will likely increase the availability of biologically limiting factors such as iron and light (Boyd and Doney, 2002). The air-sea carbon flux of seasonally ice-covered oceans is sensitive to changes in the timing of seasonal sea ice because of the balance between the potential for ventilation of CO₂-rich waters in late winter/early spring versus CO₂ draw down by high rates of biological productivity in spring/summer (Yager et al., 1995; Miller et al., 2002; Takahashi et al. 2002; Sweeney, 2003). Within the polynya, unstable upper water columns due to upwelling of modified CDW and/or glacial melt-water introduction below the euphotic zone may decrease light availability close to glaciers (Alderkamp et al.,

2012a) and enhance CO₂ outgassing. Phytoplankton assemblage composition may change (Arrigo et al., 1999), which may in turn alter carbon export efficiency (Boyd and Trull, 2007) and exert significant biogeochemical feedbacks on global climate. The near-future impacts of anthropogenic changes on ocean biology and biogeochemistry are just now being explored.

With the outstanding support of the USAP, Swedish Polar Research, and the *Palmer*, ASPIRE is moving us forward in our understanding of ecosystem change in an important polynya system. Based on ASPIRE's preliminary findings of high phytoplankton productivity, the potential for glacially derived Fe to be a source of Fe to the euphotic zone, an efficient biological pump, and signs of carbon export out of the euphotic zone, we expect that the Amundsen Sea Polynya will likely become more productive and a greater carbon sink in the short term as sea ice and ice shelf melt contribute to the light and iron requirements of the phytoplankton. However, continued dramatic changes are likely to trigger nonlinear responses that are hard to predict. At the extreme, the complete loss of sea ice, and the transformation of the polynya system to a year-round open water system (as with the Northeast Water Polynya in the Arctic), would no doubt threaten the extraordinary attributes of the Amundsen Sea Polynya.

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