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Introduction

The interdisciplinary marine system of the Amundsen Sea, Southern Ocean: Recent advances and the need for sustained observations

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1. Introduction

The Southern Ocean exerts a profound influence on the functioning of the Earth System, in part because its location and unique bathymetric configuration enable direct linkages to the other major ocean basins (Ganachaud and Wunsch, 2000; Lumpkin and Speer, 2007). It is the site of the world's largest current system, the Antarctic Circumpolar Current (ACC), which transfers waters and climatically/ecologically-important tracers between the Atlantic, Indian and Pacific Oceans (Rintoul et al., 2001). In addition to the strong horizontal connectivity, the ACC is also characterized by a vigorous overturning circulation, which upwells warm, nutrient-rich waters from intermediate depth to the surface, where they are modified by interactions with the atmosphere and cryosphere to form new water masses, some of which are lighter and others more dense (Marshall and Speer, 2012). This overturning circulation structures the Southern Ocean both horizontally and vertically, dictates the levels of its communication with the rest of the global ocean, and is a fundamental control on the sequestration of carbon from the atmosphere into the ocean interior (Sallée et al., 2012). In some locations, the upwelled waters can intrude onto the Antarctic shelves, supplying heat and nutrients to the shallower regions. This is believed to be especially effective in west Antarctica, where the southern edge of the ACC moves close to the shelf break (Martinson, 2011; Orsi et al., 1995; Thoma et al., 2008).

Several aspects of the Southern Ocean exemplify its differences from the lower-latitude seas. It is abutted to the south by the giant Antarctic ice sheet, and there are strong interactions between the comparatively warm ocean and the floating ice shelves at its periphery. Ocean-induced melting is reducing the buttressing effect of these ice shelves in particular locations, particularly in West Antarctica, which can significantly destabilize the ice sheet (Jenkins et al., 2010; Pritchard et al., 2012; Shepherd et al., 2004). The glacial discharge produced is a major freshwater source to the Southern Ocean, and it provides the marine system with iron and other nutrients needed to support biological productivity.

The Southern Ocean is also characterized by extensive seasonal sea-ice cover, which is sensitive to climatic changes via mechanisms that are complex and presently not fully understood (Stammerjohn et al., 2012). Unlike the Arctic, the Southern Ocean sea-ice field exhibits marked regional variations, with some sectors decreasing in sea-ice extent and duration, and others increasing (Turner et al., 2009). Much of West Antarctica falls into the former category, coincident with a generalized warming in recent decades. The regional changes have a major impact on water mass formation, upper ocean processes and ecological habitats (Stammerjohn et al., 2012). Overall, there has recently been a small but significant circumpolar increase in sea ice around the Antarctic, with implications for albedo, surface fluxes, ecology and climatic balances.

The Southern Ocean is characterized by productive and regionally-varying ecosystems, some levels of which are commercially exploited (e.g. Ducklow et al., 2012; Murphy et al., 2007). These are known to be climatically sensitive via changes in ocean

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temperature, circulation and sea ice, and also to respond to variations in surface irradiance, mixing and other physical and biogeochemical processes (e.g. Atkinson et al., 2004; Montes-Hugo et al., 2009; Saba et al., 2014). These biological systems can significantly alter the carbon fluxes between the Southern Ocean and the atmosphere, and hence exert an influence on global climate. The increasing sequestration of anthropogenic carbon from the atmosphere may also lead to accelerated acidification of the Southern Ocean compared with the lower latitude seas, with implications for the functioning of different levels of the ecosystem itself (Bednaršek et al., 2012).

Considering the strong influence of the Southern Ocean on the global system, the need to develop a comprehensive understanding of its interdisciplinary functioning is clear. This requires sustained observations that cover large spatial scales, and that enable researchers to fully address each of the strategic issues outlined above. However, the Southern Ocean has historically been the world's greatest data desert, as a consequence of its remote location and its hostile environment. Recently, the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR) created an international initiative, the Southern Ocean Observing System (SOOS), to facilitate the collection of the sustained marine observations required to remedy this dearth of data (Meredith et al., 2013; Rintoul et al., 2012). Whilst still at an early stage in its development, SOOS is already showing significant progress at addressing this problem.

Regionally, one sector of the Southern Ocean that has exemplified the paucity of data is the Amundsen Sea. In large part, this is because it has been remote from any nation's permanent research stations on the Antarctic continent; hence it has been visited only infrequently by research/resupply vessels. However, the Amundsen Sea has some specific characteristics that make it a key region of interest within the Southern Ocean system. Recent studies have indicated that the Thwaites Glacier in Pine Island Bay is retreating at a rate of 83 ± 5 Gt yr^{-1} and has begun to undergo early-stage collapse, with the potential for causing over 1 mm yr^{-1} of global sea level rise (Joughin et al., 2014). The nearby Getz Ice Shelf is the largest contributor to the overall volume loss of Antarctic ice shelves, with an average loss of -54 ± 5 Gt yr^{-1} (Paolo et al., 2015). Changes are believed to be due to increasing access of heat from the deep waters of the ACC to the underside of the ice shelves, via the penetration of these waters onto and across the shelf (Jacobs et al., 2011; Schmidtko et al., 2014), although this has not yet been shown in synoptic time series of basal melt and ocean temperature. This has significant consequences for global sea-level rise, a fact underlined by recent assertions that the retreat of this part of the ice sheet is irreversible (Rignot et al., 2014).

A second reason that the Amundsen Sea is a region of specific interest in the broader Southern Ocean is the presence of large polynyas that feature extremely productive plankton blooms in spring (Arrigo and van Dijken, 2003). Such events can be associated with reductions in the partial pressure of CO_2 at the ocean surface (Mu et al., 2014), and intense sedimentation events (Ducklow et al., 2008; Takahashi et al., 2002). It is hypothesized that ice shelf melting delivers nutrients and stabilizes the water-column, thus allowing cells to overcome light limitation; accordingly, whether future productivity rates will remain as high is an open question that reflects the complexities of circulation in the polynya and below the ice shelf. Continued and perhaps even increased ice melt has the potential to alter these physical and biological feedbacks, motivating focused programs to quantify these mechanisms and define the trajectory of the ecosystem in the coming decades.

In light of the above, the Amundsen Sea has recently become the target for a number of international programs that have sought to progress our understanding of these issues. These include the United States-led Amundsen Sea Polynya International Research Expedition (ASPIRE; https://home.elementascience.org/special-features/aspire-the-amundsen-sea-polynya-international-research-expedition/), the United Kingdom-led Ice Sheet Stability (iSTAR) program, the Sweden/US Oden Southern Ocean expeditions (2007–2011) and the Korea Polar Research Institute (KOPRI) Amundsen Project that is the focus of this volume.

2. Progress in understanding the Amundsen Sea system from KOPRI expeditions

Significant recent advances in our understanding of the Amundsen Sea are highlighted herein. The observed losses on the ice sheet in the Amundsen are due primarily to thinning of the floating ice shelves (Paolo et al., 2015) caused by basal melting driven by warm ocean water that floods the continental shelf and

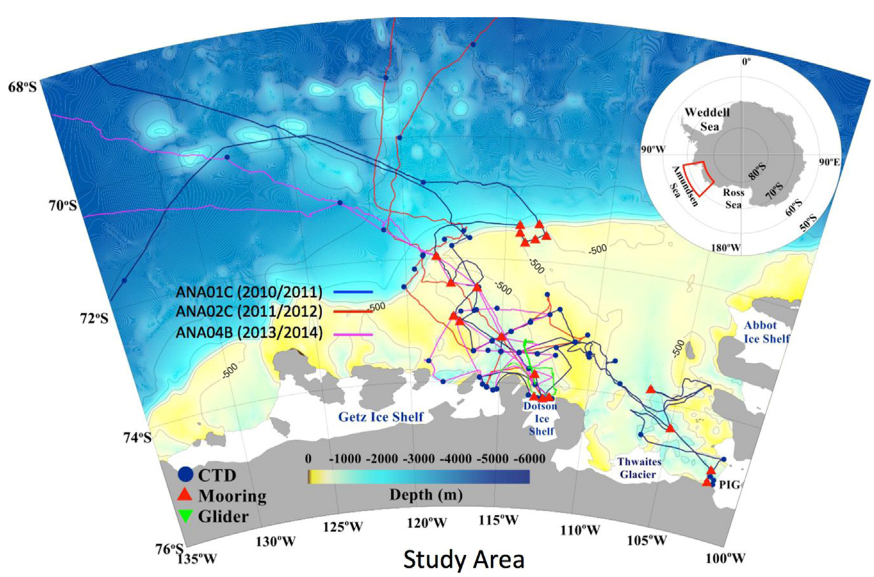

Fig. 1. Past cruise tracks and stations occupied in the study area. The long-term mooring observation program is a combined product of the research collaboration among KOPRI, Gothenburg University, British Antarctic Survey, and ASPIRE. Rutgers University contributed glider surveys and Fluorescence Induction and Relaxation (FIRe) measurements.

accesses the ice shelf cavities via submarine channels in the seafloor (Jacobs et al., 2011; Pritchard et al., 2012). Warm dense inflows have been observed on the Amundsen Sea shelf (Assmann et al., 2013; Ha et al., 2014; Jacobs et al., 2011; Wåhlin et al., 2010; Walker et al., 2007) and several processes are hypothesized to regulate the inflow of warm deep water. Putative drivers transporting warm water onto the shelf include eastward undercurrents (Chavanne et al., 2010; Walker et al., 2013), bottom Ekman transports (Wåhlin et al., 2012), eddies (Thompson et al., 2014) and wind (Assmann et al., 2013; Thoma et al., 2008; Wåhlin et al., 2013). During the KOPRI expeditions, Kalén et al. (2015) document that, contrary to previous results based on shorter records, the circulation on the shelf is primarily barotropic (i.e., vertically uniform) in nature. This means that barotropic currents, typically circulating towards the glaciers on the eastern flank of the deep troughs and away from the glaciers on the western side (Ha et al., 2014), are responsible for moving water towards and away from the glaciers. The resulting heat flux towards the glaciers is a by-product of this large-scale circulation and not a cause of it. The strength of the barotropic circulation (likely determined by the wind) in combination with the water temperature sets the levels of oceanic heat available to melt the glaciers.

The impact of meltwater from the glaciers was investigated by Miles et al. (2015), who used an autonomous ocean glider to document the characteristics of an outflow plume from below the western flank of the Dotson Ice Shelf. Optical data suggested that the turbid jet was sourced from the overlying glacier rather than resuspension from the seafloor. This suggests that particulate iron, and potentially phytoplankton primary productivity, are intrinsically linked to the magnitude and duration of sub-glacial melt from the intrusions of warm, deep water from the ACC onto the shelf. This has a range of implications of how the outflow drives the large phytoplankton blooms that have been observed by past studies in this region (Alderkamp et al., 2015; Schofield et al., 2015).

Carbon flow through the marine food web is a key pathway of its biogeochemical cycle, and an important topic of ecosystem studies. While bulk amount of carbon is routinely referred to in presenting the major exchanges, biochemical properties of the organic carbon govern the efficiency of the carbon flow in the cycle, because they determine the nutritional value and degradability (Joo et al., 2007; Lindqvist and Lignell, 1997).

Concentrations and distribution of colored dissolved organic matter (CDOM), an optically active fraction of the bulk dissolved organic carbon, were investigated in relation to the phytoplankton composition by Lee et al. (2015). They found the highest levels concentrations of CDOM reported from Antarctica to date, and suggested that this reflected the very high stocks of *Phaeocystis antarctica* in the polynya and their significant role in the carbon flow.

By analyzing the macromolecular composition of the phytoplankton, Kim et al. (2015a) report the algal assemblage in the Amundsen polynya is a protein-rich food source. The ecosystem may not be limited for nitrogen overall, instead the limitation may occur only seasonally during peak blooms. This observation is supported by another study (Song et al., 2015) that used stable isotopes to trace the photosynthesize carbon, and showed that allocations of carbon to cellular protein resulted in high protein production by phytoplankton.

Microzooplankton composition and grazing impact drive top-down control on phytoplankton in pelagic ecosystems (Strom et al., 2007). Microzooplankton grazing may restructure phytoplankton composition when it is selective, and thereby influence the structure of the food web via top-down control (Burkill et al., 1987; Calbet and Landry, 2004; Yang et al., 2012). The Amundsen Sea, which is historically known as a region of multi-year sea ice, is currently undergoing sea ice recession (Jacobs and Comiso, 1993). Rapid melting of glaciers and losses of sea ice in this area may profoundly alter ecosystem, in terms of biodiversity and species distributions, by changing pathways of energy flow, and result in changes in habitat conditions and community composition (Griffiths, 2010; Jiang et al., 2014).

In the Amundsen sea, phytoplankton biomass appears to be controlled by the seasonal recession of the sea ice and the formation of the polynya (Arrigo et al., 2012). Decreasing sea ice, coupled with increasing solar radiation and surface mixing, could lead to shifts in phytoplankton composition and production, which subsequently would affect the microzooplankton and other grazers in the higher trophic levels.

Grazing impact by microzooplankton on primary producers in the Southern Ocean is extremely variable (Garrison, 1991); 0% to $>700\%$ of phytoplankton primary production (PP) being consumed daily across the systems. In the marginal ice zone near Davis Station, East Antarctica, microzooplankton exerts considerable grazing pressure on phytoplankton, removing up to 762% of primary production (Pearce et al., 2008), whereas Caron et al. (2000) assessed that microzooplankton grazing rate in the Ross Sea was sometimes undetectable. The great variability was apparently due to very low water temperatures and the presence of sea ice, which constrain grazer activity, as well as food (phytoplankton) availability to the grazers.

Jiang et al. (2015) reports that the ciliate biomass in the Amundsen Sea was correlated with chlorophyll, and that the community structure varied with the sea ice coverage, whilst Yang et al. (2015) showed the dominant phytoplankton species varied with the sea ice condition, which subsequently led to a shift of the grazers from ciliates in the sea ice zone to flagellates in the central polynya. This pair of studies demonstrated that the link of sea ice to microzooplankton was mediated by phytoplankton, and suggested that the microzooplankton is a major consumer of primary production, and an important component of the carbon cycle in the Amundsen Sea.

A study that combined fatty acid and stable isotope analyses (Ko et al., 2015) elucidated the food source of two major Euphausia species; *Euphausia superba* fed mostly on phytoplankton cells, while *E. crystallorophias* (ice krill) showed a more carnivorous tendency, deriving the energy from the microbial loop and associated consumers. The paper discusses the relative importance of the two krill species in the trophodynamics and energy flow under different sea ice regimes and habitat preferences.

La et al. (2015) conducted acoustic analyses on volume-backscatter data, and demonstrated that *E. crystallorophias* has an acoustic fingerprint unique from other Southern Ocean zooplankton species including *E. superba*. This has the potential to improve the acoustic identification and density estimation of ice krill in the high-latitude waters around the Antarctic.

Starting from an almost complete lack of knowledge prior to 2010, except for that derived from remotely sensed ocean color (Arrigo and van Dijken, 2003), substantial progress has been made in understanding the biogeochemical system of the Amundsen Sea polynya. Net primary production rates (NPP) were very high and variable (84–333 mmol C m^{-2} d^{-1}) near the peak of the phytoplankton bloom within the polynya during the ASPIRE cruise in 2010–2011. The high NPP appears to be supported by transport of iron from melting glaciers (Alderkamp et al., 2015; Gerringa et al., 2012; Sherrell et al., 2015). This mechanism may be especially important in the Amundsen Sea, a region of increased ice mass loss (Rignot et al., 2008). Net community production (NCP), the source of export as well as sustenance for upper trophic levels, appeared to be 40–60% of the NPP (Yager et al., submitted). This ratio, a key indicator of ecosystem production efficiency, is similar to a range of other ocean ecosystems including the subtropical gyres (Quay et al., 2010). This similarity across such widely divergent biomes suggests the existence of heretofore-unappreciated common structures in ocean biogeochemical systems. Recent measurements by the KOPRI expeditions (Hyun et al., 2015; Kim et al., 2015d) add further support to the above observations that not all the NCP was exported. The ratio of export to NCP derived from floating sediment traps averaged 0.6, with the remainder persisting as accumulated biomass and detritus in the surface layer (Yager et al., submitted). Accumulated biomass is the hallmark of phytoplankton blooms, so this is not surprising; but it might be expected that over the course of a year, this imbalance would disappear. However accounting for all the carbon fluxes in the nearshore region at Palmer Station Antarctica over a full growing season failed to resolve the imbalance (Stukel et al., 2015). Further studies in the Amundsen Sea polynya and elsewhere may suggest if this imbalance in the local carbon budget is unique to Antarctica or a more general phenomenon.

Although the export and NCP fractions were typical of other ocean ecosystems (Henson et al., 2012), only about 1% of the export flux leaving the upper 50–100 m survived to be captured in moored sediment traps at 350–400 m (Ducklow et al., 2015; Kim et al., 2015b). Organic degradation in the Amundsen shelf sediment measured by oxygen consumption (aerobic respiration) and sulfate reduction (anaerobic) accounted for only about 1% of the primary production in the surface water (Kim et al. 2015d). Their study showed that most (90%) of the degradation was by aerobic processes, and that the benthic nutrient flux was low. This study also indicated that most of the organic carbon from primary production does not reach the sediment, being degraded or respired in the water column. These results indicate that the Amundsen Sea polynya system is highly inefficient at transporting carbon below the upper few hundred meters, and likely not an important site of carbon storage.

The particle flux appears to be consumed rapidly by bacteria in the water column (Williams et al., submitted). Hyun et al. (2015) investigated heterotrophic bacterial production rates at several locations in the polynya region, and related bacterial abundance and activity to temperature and chlorophyll, finding a strong coupling between bacterial and phytoplankton dynamics. Bacterial production was a rather high fraction of photosynthesis rates (17%) in contrast to several other regions around Antarctica. High bacterial activity at the expense of phytoplankton stocks may be one reason that particle fluxes in the region are low. Indeed, the summertime bacterial community in the Amundsen Sea polynya is a highly adapted and modified, low-diversity assemblage of bacteria optimized for growth on enhanced organic matter derived from phytoplankton blooms, especially *Phaeocystis antarctica*, the dominant species in the polynya.

Combinations of molecular analyses and biochemical characterizations of bacterial communities revealed new insights. Choi et al. (2015) found high copy numbers of genes responsible for N_2 production in sediments, which were comparable to those found in organic-rich environments. However, the actual N_2 production was lower than the levels measured in other polar regions. Another paper (Choi et al., 2015) investigated the 16S sequence diversity of the bacterioplankton assemblage in the polynya, along with the metabolic capabilities of the isolates (obtained from the sampled seawater) that represent the major phylogenetic clades (obtained from the diversity analyses). Use of both culture-dependent and -independent methods in parallel proved very powerful in dissecting bacterial communities and microbial process.

Kim. et al. (2015c) investigated the accumulation rates of the sediment organic carbon in and out of the Amundsen polynya. The accumulation in the most recent 3.1–4.7 kyr was generally linear, however they found an abrupt change at 4.7 kyr BP (before present), with the more recent rate being 20 times higher than the preceding rate back to 15.7 kyr BP. The paper discusses possible cause of the sudden shift, the origin of the organic matter and the relevant sedimentation processes, in the context of the carbon cycle.

Collectively, these contributions provide a substantial step forward in our understanding of the multi-disciplinary marine system of the Amundsen Sea, how it interacts with the atmosphere and cryosphere, and how it influences the Southern Ocean and beyond.

3. Conclusions

The KOPRI Amundsen Project, a multidisciplinary program that investigates the western Antarctic warming and its impact on ecosystem and biogeochemical cycles, was launched in 2010 and successfully carried out 3 field expeditions to date (Fig. 1). Upon completing its early stage research goals, the project will enter its third phase in 2017. The advances reported in this volume individually and collectively add significant new knowledge to our overall comprehension of the functioning of this globally-important ocean. However, as with any successful time-bound program, they have raised further intriguing and compelling questions that require answers.

In addition to the ongoing work packages, developments to the project to address these questions include the geographical expansion of the research area into new territories, in particular the Thwaites glacier tongue and both the eastern and pristine western entrances to the Getz Ice Shelf cavity. Further expansion includes incorporation of the French and US research groups that joined in 2014 to study the heat flux through the Udintsev Fracture Zone in the ACC, and the Norwegian group that joined in 2015 to reinforce the Korea–UK–Sweden mooring network in the Amundsen continental shelf area. Phase-sensitive radars are to be deployed on ice shelves in the Amundsen coastal area for sustained observation of their thickness changes (part of the UK-led SOOS NECKLACE program aimed at obtaining synoptic time series of basal melt and oceanic temperature), and sub-ice-shelf exploration with autonomous underwater vehicles is planned for the near future. All of these research activities require multi-year investigations, and subsequently multi-year commitment from KOPRI to its Amundsen Project, which now constitutes the focus of the primary multi-national platform in the region.

The need for an international, sustained ocean observing network in the Amundsen Sea is thus well established, with such a network designed to deliver the interdisciplinary marine data required for the indefinite future. This modus operandi is exemplified by the moorings systems that have been maintained in the Amundsen Sea for several years now – the data from these is priceless, but its collection and continuity has required strong cooperation between nations, and flexibility from the operators of Antarctic research vessels. Of course, as ocean technology continues to evolve and mature, many of the measurements that currently can only be made from research vessels will be moved to autonomous platforms, such as ice-capable gliders capable of navigating year-round under sea ice. Nonetheless, these vehicles still require deployment and recovery from ships or land stations, and so the need for research ships to access the region will remain for the foreseeable future. Both autonomous and traditional expeditions to the Amundsen Sea will require international coordination in future, if a genuinely interdisciplinary and comprehensive ocean observing system is to be maintained.

In summary, the Amundsen Sea is known to be a critically important area within the Southern Ocean, and one that requires substantial ongoing research effort to fully understand the controls it exerts on the Earth System. The papers contained in this volume each represent significant advances in this area, but observational programs are now needed that can be sustained for the indefinite future. The scale of this problem is such that requires this effort to be a genuine, coordinated, international effort. The driver is now for the research community and SOOS to engage with developing this effort.

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