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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

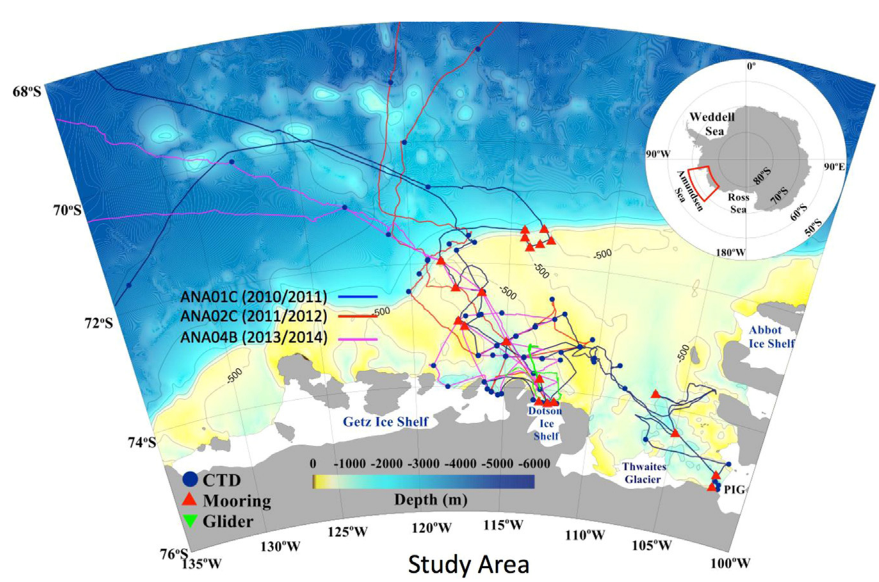

Fig. 1. Past cruise tracks and stations occupied in the study area. The long-term mooring observation program is a combined product of the research collaboration among KOPRI, Gothenburg University, British Antarctic Survey, and ASPIRE. Rutgers University contributed glider surveys and Fluorescence Induction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