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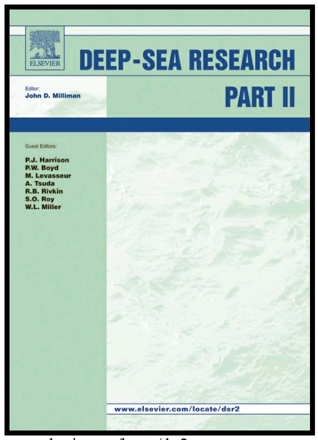

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Marine studies at the western Antarctic Peninsula: priorities, progress and prognosis

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1. Introduction: why Antarctica?

Since its discovery and the early heroic age of its exploration, Antarctica has held a fascination for scientists and the general public alike. Being an untouched wilderness, images of Antarctica inspired researchers to survey it for new discoveries that had the potential to radically reshape understanding of our planet and the life that it inhabits. Many of the early expeditions that charted Antarctica carried scientific parties, eager to increase the sum of human knowledge in addition to testing human endurance in the harshest of environments.

Vast progress has been made since these early days. Today, satellite-borne sensors provide routine updates on the weather and climate of Antarctica, as well as the glaciological conditions of its ice and the circulation and surface properties of the Southern Ocean surrounding it. Autonomous instruments provide vital data series from remote locations, and permanent research stations are occupied year-round on the continent, especially along the periphery of its coastline. Antarctica and the Southern Ocean are now better observed than at any time in human history. However, compared with the rest of the planet, these regions still stand out as being the least comprehensively measured, and containing some of the biggest knowledge gaps.

These are critical shortcomings. It is now universally recognised that Antarctica and the Southern Ocean exert strong influences on the whole operation of Planet Earth, and that changes in the polar system can have strong repercussions across the globe. There are a number of key mechanisms and processes that enable this influence to be exerted, and understanding them, their interactions and their feedbacks, are high priorities across a range of disciplines.

Against this background of a need for enhanced strategic data collection and research, an innovative international collaboration at the Antarctic Peninsula has recently been developed (see Section 3 below). This UK-Netherlands partnership at Rothera Research Station (Fig. 1) has enhanced and accelerated scientific progress beyond the level that would otherwise have been possible. This new collaboration sits within the context of increasing multinational cooperation in Antarctic research, and inspired the initiation of this *Deep-Sea Research II* Special Issue. The papers included have been selected to showcase the current state of international cooperation in marine research along the Antarctic Peninsula.

2. Why the Antarctic Peninsula?

The Antarctic Peninsula is separated from South America by Drake Passage, the narrowest constriction through which flows the Antarctic Circumpolar Current (ACC) (Orsi et al., 1995). This proximity has led to the Peninsula being the most inhabited part of Antarctica. Due partly to the juxtaposition of the ACC (Fig. 1), the climate on the western side of the Peninsula is much warmer than that on the eastern side, and the sea ice is much less extensive. This results in greater accessibility of the ocean adjacent to the Western Antarctic Peninsula (WAP), and has led to it being the centre for some of the most expansive and insightful research programmes in the Southern Ocean.

Scientifically, a strong benefit of working at the WAP has derived from it being a region of very rapid environmental change. During the second half of the twentieth century, the surface WAP atmosphere warmed more rapidly than any other region in the Southern Hemisphere, and at rates rivalled only by certain locations in the northern high latitudes (Turner et al., 2005). Other profound changes in the physical environment include a remarkable diminution of the sea ice and a dramatic shortening of the sea-ice season (by well over two months; Stammerjohn et al., 2012), and an increase in precipitation, with snowfall rates having doubled in some locations over the course of the twentieth century (Thomas et al., 2008). A further profound change that has been observed is the retreat of the majority of glaciers and the collapse of ice shelves along the WAP; this was initially attributed primarily to the atmospheric warming, but was recently shown to be driven predominantly by the warming of the deep ocean associated with greater intrusion of warm water from the ACC onto and across the WAP shelf (Cook et al., 2016). Figure 2 illustrates schematically some of the most significant changes to the WAP physical environment.

These changes in the physical environment of the WAP, and the responses in the ecosystem that they induce, are of profound importance. Whilst not the dominant term in the cryospheric contribution to sea level rise, it is estimated that the WAP glaciers contribute as much to sea level rise as all Alaskan glaciers combined (Ivins et al., 2011). The loss of sea ice at the WAP and across the Bellingshausen Sea is one of two “nodes” of rapid sea-ice change around Antarctica, which largely compensate each other and result in a very moderate increase in circumpolar sea-ice extent (e.g. Parkinson and Cavalieri, 2012).

Such physical changes have profound implications for biogeochemical cycling of climatically-relevant elements and habitat suitability for a range of key marine species. For example, sea ice harbors a very condensed source of algae that plays key roles in carbon drawdown and production of climatically-important gases such as dimethyl sulphide and halocarbons (Vancoppenolle et al., 2013). The bottom community consists primarily of diatoms and forms a rich food resource for higher trophic levels, including Antarctic krill (*Euphausia superba*), which is a key species in regional foodwebs and for which the WAP is an important breeding and nursery ground (Murphy et al., 2004). In addition, pelagic productivity is linked to the wax and wane of sea ice through various biological and physical processes and with rapid changes in timing, extent and duration of sea ice in the WAP area, large changes are observed in primary production and phytoplankton composition, with cascading effects on the food web (Vernet et al., 2008; Montes-Hugo et al., 2009; Ducklow et al., 2012).

Taken together, the WAP has offered marine scientists an exceptional opportunity to progress knowledge and understanding of the dynamics of a changing system in unparalleled detail, and hence to gain insight into how the rest of the Southern Ocean might change in future as environmental change progresses. Notwithstanding, the WAP is a complex system that still has the capacity to surprise, as illustrated by the recent observation that the WAP atmosphere has not warmed since approximately the turn of the century, and has even cooled in some locations (Turner et al., 2016). This hiatus in the WAP warming trend, albeit one of (presently) unknown duration, will certainly have ramifications for the other elements of the interdisciplinary WAP system, and these are the focus of ongoing research. Such examples highlight the complexity of the regional-scale system with which we are dealing, and, above all, stress the need to better understand the forcing of the WAP system and its multi-disciplinary responses, so that the scientific and societal consequences thereof can be better ascertained.

3. How were the new studies done?

The research presented in this Special Issue has been enabled via three interlinked initiatives at the WAP. One of these is the Rothera Time Series (RaTS), which is a sustained program that the British Antarctic Survey (BAS) conducts from its Rothera Research Station on Adelaide Island at the northern end of Marguerite Bay (Fig. 1). RaTS commenced in 1997, and has subsequently maintained quasi-weekly measurements of the marine environment in Ryder Bay adjacent to Rothera. These measurements have been taken from rigid inflatable boats or through a hole cut in the sea ice, and include full-depth (~500 m) profiles of temperature, salinity, fluorescence, and photosynthetically-active radiation obtained with a Conductivity-Temperature-Depth (CTD) profiler, with discrete Niskin bottle sampling for size-fractionated chlorophyll, nitrate, silicate, phosphate, ammonia, dissolved organic carbon and the stable isotopes of oxygen. This continuity of sampling across the winter months is almost unique in the Antarctic context, and has enabled some particular insights into the key processes that shape and structure this coastal environment.

Figure 3 shows recently-updated series of RaTS temperature, salinity and chlorophyll. A great number of studies have investigated different aspects of the nature and variability of these (and other) RaTS data in detail, including unravelling the response of the WAP ocean to El Niño/Southern Oscillation (ENSO) forcing, the impacts of changes in the Southern Annular Mode (SAM), the freshwater budget, and the role of wintertime processes in controlling the timing and magnitude of the spring bloom (e.g. Meredith et al. 2004; Clarke et al, 2008; Venables et al., 2013; Meredith et al., 2013; etc.). Diverse marine biological projects are connected to RaTS, with particular emphasis on benthic ecology and the impacts of environmental disturbance and change (e.g. Clarke et al., 2012; and refs therein).

A central ethos of RaTS is that, in addition to being a unique and valuable time series in its own right, it provides the logistical framework and scientific context to which other, usually finite-duration, process studies can connect (e.g. Wallace et al., 2008; Annett et al., 2015; Hughes et al., 2012; Legge et al., 2015; etc.). This modus operandi was recently extended with the creation of a Netherlands-UK partnership in Antarctic science. A new Memorandum of Understanding paved the way for a major innovation that connects to and enhances science at Rothera via the development and deployment of a novel laboratory complex, using modular and flexible laboratory containers (Fig. 4). The docking station houses four 20-foot ISO-standard high cube containers, each of which contains a different laboratory. Upon installation, connection to water, drainage, power and internet are all that is required for operation. Technical features such as energy-efficient heat-pump installations, fully-insulated walls, floor heating for constant temperature and the transportable nature of the facility all contribute to minimize the environmental footprint of the facility. Solar panels provide 20-30% of total energy usage of the facility on a yearly basis, and up to 50% in summer. Internet connections allow remote monitoring and operation by technicians in the Netherlands. The containers are flexible and can be installed and used as required, and renewed or removed when necessary. They can also be put onboard research ships for use during expeditions. The four containers currently at Rothera are designed for various purposes: Lab 1 is suitable for the use of various analytical instruments that need to be run at room temperature; Lab 2 is utilized for processing water samples and performing biological experiments at *in situ* temperature; Lab 3 is equipped with a culture cabinet with plasma lamps that provide daylight spectrum and with a mass spectrometer; Lab 4 is a clean-room laboratory suitable for trace metal analysis and for measuring low concentrations of contaminants. It is equipped with special filters in the air-processing system to ensure that the air entering the container is completely particle free. Transportable research lab facilities provide an effective and efficient approach for undertaking scientific research projects in challenging environments, and form the potential basis of a new means of undertaking scientific projects including exchanging laboratory modules between research stations around Antarctica, between research ships, and elsewhere. Of the ten Dutch-led projects that have been conducted so far, four present their first results in this Special Issue (Bown et al., this issue; Jones et al., this issue; Rozema et al., this issue; van Wessem et al., this issue).

In addition, RaTS also connects strongly to the Palmer Long-Term Ecological Research (LTER) programme. This is a United States sustained research programme that operates from Palmer Station on Anvers Island (Fig. 1), where summer-season time series data comparable to RaTS are collected. In addition, Palmer LTER conducts major cruises across the WAP each summer from the ARSV *Laurence M. Gould*, providing strong spatial coverage of the variables and processes being considered and also maintains a network of moorings across the WAP shelf. In recent years, Palmer LTER has pioneered the use of ocean gliders at the WAP to increase the spatio-temporal coverage of data collection; BAS has commenced such glider deployments from Rothera and autonomous glider flights between the two research stations have been successfully completed.

It is important to note that the papers in this Special Issue were derived from the interworking of these linked initiatives: the breadth and depth of research progress showcased here could not have been made by these programmes working in isolation. This is regarded as a model for future progress, which will require sustained and increased international collaboration for the major research goals to be achieved (Meredith et al., 2013).

4. What do the new studies tell us, and why are they important?

As noted above, the comparatively warm climate of the WAP is due at least partly to the proximity of the ACC. Unlike other sectors of Antarctica, where the ACC is separated from the shelf region by expansive subpolar gyres, the ACC lies immediately adjacent to the shelf break at the WAP. This enables Circumpolar Deep Water (CDW) to intrude from the open ocean onto the shelf via deep, glacially-scoured canyons, and hence provide a source of heat, nutrients and other climatically- and ecologically-important properties to the WAP system. Venables et al. (this issue) used data from underwater ocean gliders to study in detail the transformation of this CDW as it flows up a canyon toward Rothera. They found that the deep waters tend to pool behind topographic obstacles that lie across the trough, and that major transformations of these waters occur as they spill over the obstacles and descend down the topography on the other side. The induced mixing extends high in the water column, and has significance for the vertical distribution of benthic-derived tracers, in addition to controlling the properties of the CDW that ultimately reach the near-coastal locations. Given the known importance of the CDW as a heat source for melting WAP glaciers, this work has profound significance for better constraining future projections of cryospheric change here.

Further information on the mechanisms of ocean mixing is provided by Brearley et al. (this issue), who used velocity data from a mooring deployed in northern Marguerite Bay along with hydrographic profile data from the RaTS programme to investigate the rates and variability of vertical diffusivity. Using 2.5 years of data, they quantified diffusivity in the layer between the CDW and the overlying Antarctic Surface Water, and found that the mixing supports a mean upward heat flux of approximately 1 W/m^2, with values peaking soon after winter fast ice disintegrates. They also found that whilst tidally-driven mixing occurs year-round at the RaTS site, much of the observed mixing is driven directly by storms, and that this mixing is heavily suppressed during periods of fast ice cover. They speculate that the rapid retreat of sea ice at the WAP, with progressively fewer winters with prolonged fast ice now occurring, may be leading toward a regime of greater wind-induced mixing.

A pair of papers provide detailed investigations of the freshwater budget of the WAP. This is important for several reasons, including the supply of micronutrients to the ocean via glacial melt, potential impacts on sea level and ocean circulation, and stabilization of the upper ocean with impacts on primary production. The first of these studies (Van Wessem et al., this issue) analysed the components of the freshwater budget in a high-resolution regional atmospheric climate model, and found that snowfall was the largest component in the atmospheric contribution to freshwater delivery in the WAP region. They demonstrated that snowfall rates were elevated at the coastal WAP due to orographic effects, and remained at significant levels out to the shelf break and beyond. It was also found that rainfall was an order of magnitude smaller than snowfall and had different seasonality, and a strong dependence of precipitation on ENSO and SAM in the model was found. Van Wessem et al. (this issue) also investigated glacial discharge to the ocean, by assuming a balance with snow accumulation over the different glacial drainage systems of the WAP. They found the largest glacial discharge around Adelaide Island, Anvers Island and southern Palmer Land, with a minimum in Marguerite Bay and the northern WAP.

Meredith et al. (this issue) investigated the freshwater budget of the WAP with an observational approach, using an isotopic tracer to quantify separately the melt from sea ice and freshwater inputs from meteoric sources (glacial discharge and precipitation combined). Data from four Palmer LTER cruises were used, and sea-ice melt was found to vary from a minimum in 2011 of around 0 % up to a maximum in 2014 of around 4-5 %. As with Van Wessem et al. (this issue), the effects of both ENSO and SAM on the distributions of sea-ice melt and meteoric water were profound, with variations in the meridional wind being especially important in controlling the magnitude of the freshwater injection and its fate. It was found that the RaTS isotope series reproduced well the temporal progression of sea-ice melt as seen in the shelf-wide Palmer LTER cruise data, but less well the meteoric water changes; this was ascribed to the combined influence of local glacial inputs and precipitation effects.

The physical forcings and processes investigated in the above studies each have strong potential consequences for the marine biogeochemical system. Such potential impacts and the role of biological processes were studied by Henley et al. (this issue), with a view to understanding the role of nutrient supply, uptake and cycling in influencing the high primary production on the WAP continental shelf. Using five years of data, they quantified the seasonal nitrate uptake associated with primary production and found that it equated to a carbon uptake of 146 g C m^{-2} yr^{-1}. They noted that interannual changes in nutrient utilization related strongly to winter sea-ice duration and the intensity of upper ocean mixing, suggesting a sensitivity to climatic change via physical processes. Overall, they found that surface ocean nutrient inventories are affected by strong recycling in the water column, meltwater dilution and sea-ice processes.

A relatively new method for quantifying the controls on the carbon cycle is the simultaneous measurement of O_2, Ar and pCO_2 in underway systems. In two companion papers, Eveleth et al. (this issue a,b) explore this method to unravel the relative contribution of biological and physical processes to the total O_2 and pCO_2 signals. In their first paper, Eveleth et al (this issue a) assess the magnitude and spatial scales of variability. Using high-resolution data from Palmer LTER cruises in 2012-2014 and comparing dynamics on the WAP with open-ocean conditions in Drake Passage, they quantified the physical contribution to the signal. In the southern onshore region, the O_2 signal was significantly affected by physical contributions from ice melt/freeze processes and warming. In Drake Passage, ΔO_2/Ar and pCO_2 were much nearer to atmospheric equilibrium, again indicating physical rather than biological control.

In their second paper, Eveleth et al. (this issue b) use this method to investigate the controls on primary production at the WAP and produce estimates of net community production (NCP) at high spatial resolution from the Palmer LTER cruises. They found substantial spatial variability with strong interannual changes superposed. They also found a significant relationship between NCP and meteoric water content derived as per Meredith et al. (this issue), and suggested that this may be due to micronutrient supply by glacial melt, or impacts of the freshwater on stratification. Each of these could have strong climatic modulations as the amount of meteoric water at the WAP changes in the coming decades. Eveleth et al. (this issue b) also noted that elevated levels of NCP coincided with the location of submarine canyons at the WAP, suggestive that deep-water processes and topographically-induced upwelling and mixing may be significant.

The potential role of trace metals in influencing phytoplankton blooms at the WAP was investigated further by Bown et al. (this issue). Using data covering two consecutive summers at Rothera, they determined the temporal distributions in the upper ocean of six bioactive trace metals, namely iron, manganese, zinc, cadmium, labile cobalt and labile copper. Significant ranges in concentration were found, driven by phytoplankton uptake, remineralisation, and mixing driven by storm events, and strong evidence for the importance of dissolved iron in stimulating phytoplankton growth in the region was also found. It was argued that the surface water distributions of the measured trace metals were driven mainly by biological uptake and remineralisation during spring and summer, and that removal by scavenging over winter is slow compared with mixing. It was also suggested that short-lived events showing depletions of both nutrients and bio-active trace metals could induce stress in the growth of the phytoplankton.

Barium was another trace element under investigation (Pyle et al., this issue). Barium has a nutrient-like distribution and correlates with phytoplankton productivity, but the nature of the uptake processes is yet unknown. Barium is also used in various forms as a palaeoproxy for components of organic and inorganic carbon storage, and as a quasi-conservative water mass tracer. The authors studied dissolved barium (Ba_d) in conjunction with silicic acid ($Si(OH)_4$), oxygen isotopes, and salinity measurements, to determine the relative control of various coastal processes on the barium cycle throughout the water column. A clear relationship was established between dissolved barium and silicic acid, especially in diatom-rich surface waters along the WAP. Based on data collected during Pal-LTER cruises, it was concluded that barium is transported away from the surface in association with biogenic opal. The data also showed a new coastal source of barium that was not associated with glacial melt but rather seems to originate from shelf sediments.

Annett et al. (this issue) studied the impact of algal production in surface waters on the biochemical cycle of silica. A high-resolution record on particulate and dissolved silicate concentration was presented, and interpreted in relation to biological activity. The δ^{30}Si-signal as a function of diatom growth and species composition was studied in detail during a year with comparatively low chlorophyll levels at RaTS. Dissolved and particulate silicate phases reflected the dominant control of biological uptake. It was argued that a continued decline in diatom productivity along the WAP, as a consequence of the previously-observed warming trend, would likely result in an increasing unused Si inventory, which can potentially feed back into Si-limited areas, promoting diatom growth and carbon drawdown farther afield.

The isotopic signal of dissolved silicon provides information not only about the silicon cycle itself, but also about its role in oceanic carbon uptake in the modern ocean and in the past. Silicon may thus be applied as a proxy for past productivity. Cassarino et al. (this issue) described the fractionation processes that shape the isotope signal over the summer season, based on two summer time-series of silicon isotopes and silicic acid at RaTS. They show that besides the biological removal of silicate due to diatom growth, mixing and upwelling events further shape the silicon isotope signal. Their study highlights a potential challenge involved in the application of the Si-isotope signal as a proxy for past processes, as the signal appears quite sensitivity to small scale perturbations related to the heterogeneity of biological and physical processes.

The dynamics of algal growth were examined closely by Rozema et al. (this issue). They linked biological processes with oceanographic parameters over the course of a summer season at RaTS. Phytoplankton was studied by a combination of algal pigments and molecular analyses. It was found that enhanced diatom growth was linked to a decrease in the mixed layer depth, coinciding with increased glacial melt. The composition of the algal community changed over the season, but was always dominated by diatoms. The high chlorophyll levels followed a winter season with little sea ice. Their data add complexity to the standing theory that a decline in winter sea ice results in decreased chlorophyll concentrations in the following summer season. This study underlines the ongoing challenges in predicting the consequences of a decline in sea ice along the WAP.

The upper-ocean carbonate system was studied in detail in two papers contributed by Legge et al. (this issue) and Jones et al. (this issue). The former of these presents a three-year time series of dissolved inorganic carbon (DIC) and total alkalinity measurements at RaTS. A novel approach was used to calculate the main drivers of the seasonal cycle and simultaneously to investigate the mechanisms behind interannual variability in the carbonate system. The carbonate system showed a clear seasonal cycle, with primary production in summer being the dominant process resulting in low DIC concentrations, strengthened by increases in stratification due to glacial and sea-ice melt. The low fugacity of CO_2 in summer made the water column a sink of atmospheric CO_2. In winter, surface DIC increased again due to mixing with carbon-rich deeper waters and net heterotrophy. No indications for significant calcification processes were observed. It was speculated that in future, a decrease in winter sea ice could lead to an increase in surface CO_2 concentration, reducing the ocean sink of atmospheric CO_2 and reducing pH and the saturation state of calcium carbonate.

The study by Jones et al. (this issue) focuses on the spatial variability of ocean pH and calcium carbonate saturation states (Ω) during January-March 2014 in Ryder Bay, adjacent to Rothera. Saturation states of aragonite in surface water were strongly influenced by biological carbon uptake along the glaciated coast, resulting in high near-shore pH (~8.5) and aragonite supersaturation states ($\Omega > 3$). Large DIC summertime drawdown was amplified by sea-ice melt. Dissolution of calcium carbonate minerals released from sea ice further contributed to sea surface CO_2 undersaturation. A decreased pH and $CaCO_3$ undersaturation in deep waters was the result of export of organic material and its subsequent remineralisation. Vertical mixing processes will return this low-pH water to the surface thereby reducing the capacity for CO_2 uptake. In this polar area, the seasonality in pH and aragonite saturation may thus further enhance susceptibility of the seasonal surface layer to ocean acidification upon increased uptake of anthropogenic CO_2.

5. How should future progress be made?

The papers highlighted in this Special Issue collectively represent a significant advance in the understanding of the marine system at the WAP, and its response to environmental change. Many significant gaps in our knowledge remain, however, and it is vital that the ongoing observational programmes are sustained, with complementary targeted process studies adding to them where extra mechanistic and dynamical understanding is required. Such investigations are increasingly international in context, and there are several areas where special foci for research should be placed.

One of the main drivers for sustained scientific activity at the WAP has been its remarkable rates of environmental change, including (but certainly not limited to) a warming atmosphere, retreating sea ice, shrinking glaciers, and warming ocean. Whilst these phenomena have led to the WAP being a superb "natural laboratory" in which to study the response of the marine system to climatic change, it has frequently been challenging to discern causal relationships. For example, for many years it was assumed that the atmospheric warming was the primary driver for glacial loss at the WAP, since both were occurring synchronously, and only recently was it revealed that the concurrent warming of the deep ocean has been the main causal factor. The recently-observed pause in the atmospheric warming at the WAP (Turner et al., 2016) presents scientists with an opportunity: natural variability has, in effect, turned off one of the potential drivers for change, and studying the response of the physical and biological ocean system during this period has the potential to reveal key information concerning the causality of potential driving mechanisms.

More generally, it is clear that the climate of the WAP contains a level of complexity that is still insufficiently understood. The exact cause of the rapid warming that occurred during the second half of the twentieth century is still subject to ongoing debate, and there are open questions concerning the current pause in that warming, including its likely duration, magnitude and the nature of a possible resumption of warming. Improved predictive skill is required, but this needs better representation of processes in the regional and global models that are used. Sustained oceanic, atmospheric and cryospheric time series are vital for this, to enable regional and global models to be developed and tested in the most robust way.

A key shortcoming in the current marine observing network at the WAP is the comparative lack of wintertime data. Many important physical and biological processes occur in winter, and the absence of *in situ* observations of them over large parts of the WAP requires addressing. This is not a trivial challenge – whilst RaTS and Rothera infrastructure facilitate access to the ocean in winter, there are few other programmes that provide this. The road ahead involves increasing use of autonomous marine systems. Platforms such as underwater gliders are becoming more reliable and robust, though at present they are largely limited to the summer (ice-free) season. A high priority should be to extend their longevity and ice capability, by deploying networks of sound sources on the WAP shelf that will enable communication and navigation beneath the sea ice in winter. The development of new sensors for ocean gliders is also a high priority, to extend the range of non-physical measurements made.

Echoing this, from a biological and biogeochemical standpoint, a stronger emphasis on the winter and early-spring season is also needed for a better understanding of the coupling of biogeochemical processes between the sea ice, surface waters and benthic communities. A glimpse of the relationships being more complex than previously conceived stems from the observation that although a correlation of sea ice with pelagic primary production has been established and confirmed in several papers in this issue, in fact this correlation has reversed over the years 2012-2016, exemplifying the need for further understanding of causal mechanisms (e.g. Rozema et al., this issue). Also, little is known about the direct contribution of sea ice to the carbon system, e.g. through the formation of ikaite crystals during freezing and through the organic carbon stock contained in sea ice. Estimates of net community production (being the net drawdown of CO_2 from the atmosphere through biological uptake) in the WAP cover a wide range of values, 0.6-9.6 molC/m^{2}yr (Ducklow et al., 2012). Contributions of sea-ice communities to this number are still uncertain, but with standing stocks of approximately 1 molC/m^2, are potentially very significant. In-ice biogeochemical processes thus contribute to atmospheric CO_2 drawdown, to sedimentation and to the food supply for benthic communities. Quantitative estimates have been sporadic, however, and further measurement programs are needed to generate the data to alleviate this.

Other important aspects of the sea-ice system include the production of climatically-active gases such as dimethyl sulphide and various halocarbons that are produced in sea ice at levels that are orders of magnitude higher than in open ocean waters. Production of these compounds is usually associated with the melting period, and comprises a relatively short period of the year. Fluxes from the ice, and interactions with surface waters and atmosphere are largely unquantified. Research on these topics is logistically challenging, because important processes happen at times of the year when the ice becomes inaccessible. This motivates the development of new infrastructure that provides access to sea ice from land during conditions when ice itself is inaccessible.

The above examples illustrate just a few of the key challenges that face us at the WAP; needless to say, there are manifold others. For Antarctica as a whole, the priorities for future research direction have been clearly enunciated in SCAR's Horizon Scan (Kennicutt et al., 2014). For the ocean surrounding Antarctica, the recently-created Southern Ocean Observing System has formulated science goals that clearly address the importance of the Southern Ocean system in shaping global ocean circulation, with implications for climate, the global carbon cycle, sea-level rise, biodiversity and ecosystem services (SOOS; Rintoul et al., 2012; Meredith et al., 2013). SOOS has recently convened a WAP Working Group to coordinate the community view and structure its response to these. This is a key initiative: the rapid changes that have been observed at the WAP, and the developing insight into their causes and consequences, have the potential to inform our understanding of what might occur in future around the continent as greenhouse gas-driven warming progresses during this century.

In a system that is inherently interdisciplinary, structuring research programmes to complement, interconnect, and optimally deploy the limited resources available is key to garnering maximum progress. With this Special Issue, we hope to have contributed to a better understanding of one of the important Antarctic marine systems, the WAP, and to have illustrated and emphasised that long-term and collaborative studies are imperative for fulfilling the science goals of SCAR, SOOS, and all other initiatives that seek to enhance our understanding of the interdisciplinary Southern Ocean.

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References

Annett, A.L., M. Skiba, S.F. Henley, H.J. Venables, M.P. Meredith, P.J. Statham and R.S. Ganeshram. “Comparative roles of upwelling and glacial iron sources to the coastal western Antarctic Peninsula”. Marine Chemistry, 176, 21-33, 10.1016/j.marchem.2015.06.017, 2015.

Annett, A.L., S.F. Henley, H.J. Venables, M.P. Meredith, A. Clarke, B.C. Reynolds and R.S. Ganeshram. “Silica cycling and isotopic composition in northern Marguerite Bay on the rapidly-warming western Antarctic Peninsula”. Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.09.006, 2016.

Bown, J., P. Laan, S. Ossebaar, K. Bakker, P. Rozema and H. de Baar. “Bioactive trace metal time series during Austral summer in Ryder Bay, Western Antarctic Peninsula”. Deep-Sea Research II, this issue, 2016.

Brearley, J.A., M.P. Meredith, A.C. Naveira Garabato, H.J. Venables and M.E. Inall. “Controls on turbulent mixing processes on the Western Antarctic Peninsula Shelf”. *Deep-Sea Research II*, this issue, 2016.

Cassarino, L., K.R. Hendry, M.P. Meredith, H.J. Venables and C.L. De La Rocha. "Silicon isotope and silicic acid uptake in surface waters of Marguerite Bay, West Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.11.002, 2016.

Clarke, A., M.P. Meredith, M.I. Wallace, M.A. Brandon and D.N. Thomas. "Seasonal and interannual variability in temperature, chlorophyll and macronutrients in northern Marguerite Bay, Antarctica". Deep-Sea Research II (Palmer LTER Special Issue), 55, 18-19, 1988-2006, 2008.

Clarke, A., D.K.A. Barnes, T.J. Bracegirdle, H.W. Ducklow, J.C. King, M.P. Meredith, E.J. Murphy and L.S. Peck. "The impact of regional climate change on the marine ecosystem of the western Antarctic Peninsula". In *Antarctica: An Extreme Environment in a Changing World* (eds A.D. Rogers, E.J. Murphy, N.M. Johnston & A. Clarke), John Wiley & Sons, London, 2012.

Cook, A.J., P.R. Holland, M.P. Meredith, T. Murray, A. Luckman and D.G. Vaughan. "Ocean forcing of glacier retreat in the western Antarctic Peninsula". Science, 353, 6296, 10.1126/science.aae0017, 2016.

Ducklow, H.W., A. Clarke, S.C. Doney, H. Geisz, D.G. Martinson, M. Meredith, M. Montes-Hugo, O. Schofield, S.E. Stammerjohn, D. Steinberg, & W. Fraser. "Marine pelagic ecosystems: the west Antarctic Peninsula". In *Antarctica: An Extreme Environment in a Changing World* (eds A.D. Rogers, E.J. Murphy, N.M. Johnston & A. Clarke), John Wiley & Sons, London, 2012.

Eveleth, R., N. Cassar, S.C. Doney, D.R. Munro and C. Sweeney. "Biological and physical controls on O_2/Ar, Ar and pCO_2 variability at the Western Antarctic Peninsula and in the Drake Passage". Deep-Sea Research, this issue, 10.1016/j.dsr2.2016.05.002, 2016.

Eveleth, R., N. Cassar, R.M. Sherrell, M.P. Meredith, H. Ducklow, Y. Lin and Z. Li. "Ice melt influence on net community production along the Western Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.07.016, 2016b.

Hughes, C., M. Johnson, R. von Glasow, R.J. Chance, H. Atkinson, T. Souster, G.A. Lee, A. Clarke, M.P. Meredith, H.J. Venables, S.M. Turner, G. Malin and P.S. Liss. "Climate-induced change in biogenic bromine emissions from the Antarctic marine biosphere". Global Biogeochemical Cycles, 26, GB3019, 10.1029/2012GB004295, 2012.

Henley, S.F., R.S. Ganeshram, A.L. Annett, A.E. Fallick, M.P. Meredith, H.J. Venables and A. Clarke. "Macronutrient supply, uptake and recycling in the coastal ocean of the west Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.10.003, 2016.

Ivins, E.R., Watkins, M.M., Yuan, D.N., Dietrich, R., Casassa, G., Rulke, A. "On-land ice loss and glacial isostatic adjustment at the Drake Passage: 2003-2009". Journal of Geophysical Research, B02403, 116, 2156-2202, 10.1029/2010JB007607, 2011.

Jones, E.M., H.J.W. de Baar, N.M. Clargo, M. Fenton, H. Venables, S. Ossebaar and M.P. Meredith. "Ocean acidification and calcium carbonate saturation states in Ryder Bay, West Antarctic Peninsula". Deep-Sea Research II, this issue, 2016.

Kennicutt, M.C., S.L. Chown, J.J. Cassano, D. Liggett, R. Massom, L.S. Peck, S.R. Rintoul, J.V.W. Storey, D.G. Vaughan, T.J. Wilson and W.J. Sutherland. "Polar research: Six priorities for Antarctic science". Nature, 512, 7512, 23-25, 2014.

Legge, O.J., D.C.E. Bakker, M.T. Johnson, M.P. Meredith, H.J. Venables, P.J. Brown and G.A. Lee. "The Seasonal Cycle of Ocean-Atmosphere CO_2 Flux in Ryder Bay, West Antarctic Peninsula". *Geophysical Research Letters,* 42, 2934-2942, 10.1002/2015GL063796, 2015.

Legge, O.J., D.C.E. Bakker, M.P. Meredith, H.J. Venables, P.J. Brown, E.M. Jones and M.T. Johnson. "Quantifying carbonate system processes in the seasonally sea-ice covered waters of Ryder Bay, West Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.11.006, 2016.

Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. Fraser, W. Trivelpiece and S. Trivelpiece. "Effects of sea-ice extent and krill or salp dominance on the Antarctic food web". Nature 387, 897–90, 1997.

Meredith, M.P., I.A. Renfrew, A. Clarke, J.C. King and M.A. Brandon. "Impact of the 1997/98 ENSO on the upper waters of Marguerite Bay, western Antarctic Peninsula". Journal of Geophysical Research, 109(C9), C09013, 10.1029/2003JC001784, 2004.

Meredith, M.P., O. Schofield, L. Newman, E. Urban and M.D. Sparrow. "The Vision for a Southern Ocean Observing System". Current Opinion in Environmental Sustainability, 10.1016/j.cosust.2013.03.002, 2013.

Meredith, M.P., H.J. Venables, A. Clarke, H. Ducklow, M. Erickson, M.J. Leng, J. Lenaerts, M. van den Broeke. "The freshwater system west of the Antarctic Peninsula: spatial and temporal changes". Journal of Climate, 26(5), 1669-1684, 10.1175/JCLI-D-12-00246.1, 2013.

Meredith, M.P., H.J. Venables, S.E. Stammerjohn, H.W. Ducklow, D.G. Martinson, R.A. Iannuzzi, M.J. Leng, J.M. van Wessem, C.H. Reijmer and N.E. Barrand. "Changing distributions of sea ice melt and meteoric water west of the Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.04.019, 2016.

Moffat, C., R. Beardsley, W.B. Owens, and N. van Lipzig. A first description of the Antarctic Peninsula Coastal Current. Deep-Sea Research II 55, 277-293, 2008.

Montes-Hugo, M., S.C. Doney, H.W. Ducklow, W. Fraser, D. Martinson, S.E. Stammerjohn and O. Schofield. "Recent changes in phytoplankton communities associated with rapid regional climate change along the Western Antarctic Peninsula". Science, 1470, 323, 10.1126/science.1164533, 2009.

Murphy, E.J., S.E. Thorpe, J.L. Watkins and R. Hewitt. "Modeling the krill transport pathways in the Scotia Sea: spatial and environmental connections generating the seasonal distribution of krill." Deep-Sea Research II, 51, 1435–1456, doi:10.1016/j.dsr2.2004.06.019, 2004.

Orsi, A.H., T. Whitworth III and W.D. Nowlin Jr. "On the meridional extent and fronts of the Antarctic Circumpolar Current". Deep-Sea Research I. 42, 5, 641-673, 1995.

Parkinson, C. L., and D. J. Cavalieri. "Antarctic sea ice variability and trends, 1979–2010", Cryosphere, 6, 871–880, 10.5194/tc‐ 6‐ 871‐ 2012, 2012.

Pyle, K.M., K.R. Hendry, R.M. Sherrell, M.P. Meredith, H.J. Venables, M. Lagerstrom and A. Morte-Rodenas. "Coastal barium cycling at the West Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.11.010, 2016.

Rintoul S.R., M. Sparrow, M.P. Meredith, V. Wadley, K. Speer, E. Hofmann, C. Summerhayes, E. Urban, R. Bellerby. "The Southern Ocean Observing System: Initial Science and Implementation Strategy". Cambridge, U.K. Scientific Committee on Antarctic Research, 2012.

Ross, R.M., L.B. Quetin, D.G. Martinson, R.A. Ianuzzi, S.E. Stammerjohn and R.C. Smith. "Palmer LTER: Patterns of distribution of five dominant zooplankton species in the epipelagic zone west of the Antarctic Peninsula, 1993-2004." Deep-Sea Research II, 55, 2086-2105, 10.1016/j.dsr2.2008.04.037, 2008.

Rozema P.D., T. Biggs, P.A.A. Sprong, A.G.J. Buma, H.J. Venables, C. Evans, M.P. Meredith and H. Bolhuis. "Summer microbial community composition governed by upper-ocean stratification and nutrient availability in northern Marguerite Bay, Antarctica." Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.11.016, 2016.

Stammerjohn, S., R. Massom, D. Rind and D.G. Martinson. "Regions of rapid sea ice change: an inter-hemispheric seasonal comparison". Geophysical Research Letters, L06501, 39, 6, 10.1029/2012GL050874, 2012.

Thomas, E.R., G.J. Marshall, and J.R. McConnell. "A doubling in snow accumulation in the Western Antarctic Peninsula". Geophysical Research Letters, L01706, 35, 1, 10.1029/2007GL032529, 2008.

Turner, J., S.R. Colwell, G.J. Marshall, T.A. Lachlan-Cope, A.M. Carleton, P.D. Jones, V. Lagun, P.A. Reid and S. Iagovkina. "Antarctic climate change during the last 50 years". International Journal of Climatology. 25, 3, 279-294, 10.1002/joc.1130, 2005

Turner, J., H. Lu, I. White, J.C. King, T. Phillips, J.S. Hosking, T.J. Bracegirdle, G.J. Marshall, R. Mulvaney and P. Deb. "Absence of 21st century warming on Antarctic Peninsula consistent with natural variability". Nature, 535, 411-415, 10.1038/nature18645, 2016.

Van Wessem, J.M., M.P. Meredith, C.H. Reijmer, M.R. van den Broeke and A.J. Cook. "The modeled meteoric freshwater system of the western Antarctic Peninsula". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.11.001, 2016.

Vancoppenolle, M., K.M. Meiners, C. Michel, L. Bopp, F. Brabant, G. Carnat, B. Delille, D. Lannuzel, G. Madec, S. Moreau, J.-L. Tison and P. van der Merwe. Role of sea ice in global biogeochemical cycles: emerging views and challenges. Quaternary Science Reviews, 79: 207-230. doi:10.1016/j.quascirev.2013.04.011, 2013.

Venables, H.J., A. Clarke and M.P. Meredith. "Wintertime controls on summer stratification and productivity at the western Antarctic Peninsula". Limnology and Oceanography, 58(3), 1035-1047, 10.4319/lo.2013.58.3.1035, 2013.

Venables, H.J., M.P. Meredith and J.A. Brearley. "Modification of deep waters in Marguerite Bay, western Antarctic Peninsula, caused by topographic overflows". Deep-Sea Research II, this issue, 10.1016/j.dsr2.2016.09.005, 2016.

Vernet, M., D.G. Martinson, R. Iannuzzi, S. Stammerjohn, W. Kozlowski, K. Sines, R. Smith and I. Garibotti. "Primary production within the sea-ice zone west of the Antarctic Peninsula: I—Sea ice, summer mixed layer, and irradiance". Deep-Sea Research II, 55, 18-19, 2068–2085, 10.1016/j.dsr2.2008.05.021, 2008.

Wallace, M.I., M.P. Meredith, M.A. Brandon, T.J. Sherwin, A. Dale and A. Clarke. "On the characteristics of internal tides and coastal upwelling behaviour in Marguerite Bay, west Antarctic Peninsula". Deep-Sea Research II (Palmer LTER Special Issue), 55, 18-19, 2023-2040, 2008.

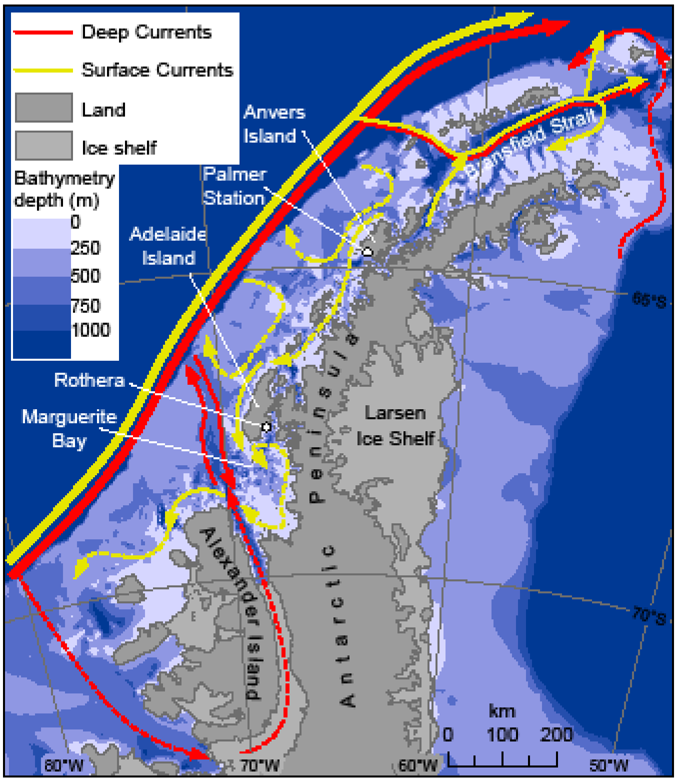
Figure Captions

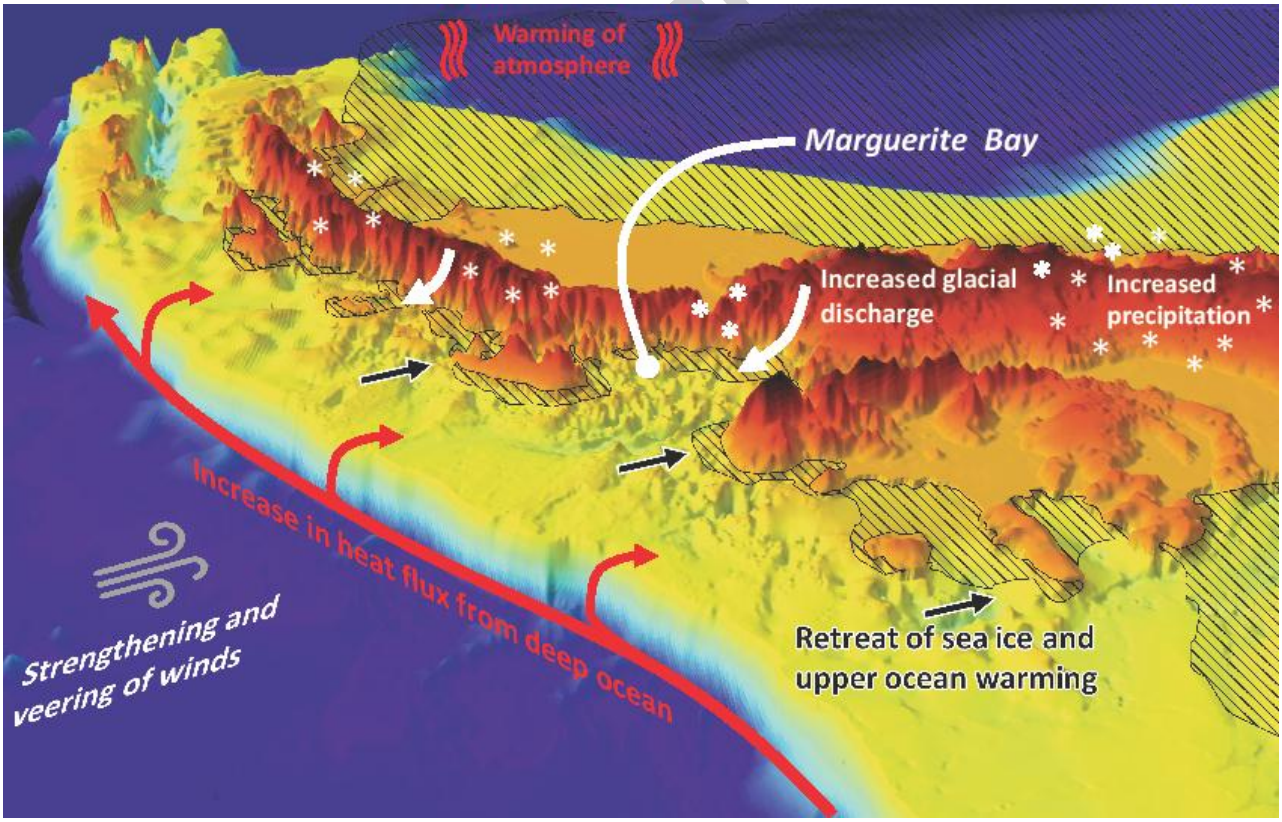
Fig. 1. Bathymetry of the Antarctic Peninsula shelf, with selected place names marked. Also shown schematically is the upper and lower-level ocean circulation, adapted from Moffat et al. (2008). Solid arrows denote circulation for which there is strong observational evidence; dashed arrows denote inferred and/or speculative patterns of flow.

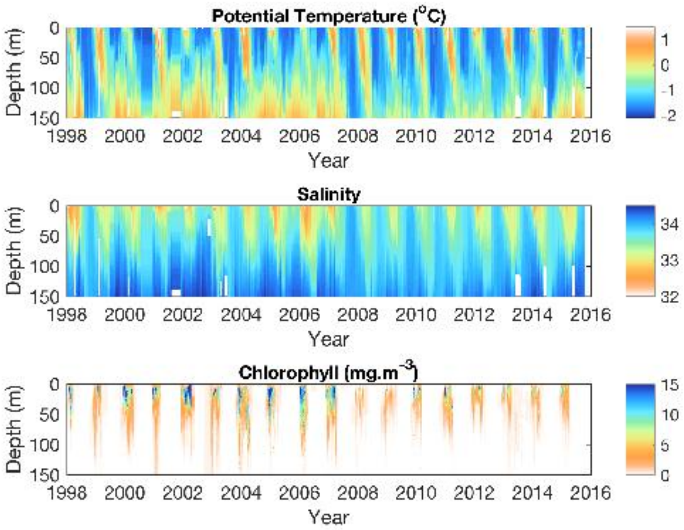
Fig. 2. Schematic of some of the major changes to the WAP environment that occurred during the second half of the 20th century.

Fig. 3. Time series of potential temperature, salinity and chlorophyll from the upper layers of the Rothera Time Series (RaTS) in Ryder Bay, West Antarctic Peninsula (Figure 1).

Fig. 4. The Dutch "Dirck Gerritsz Laboratory" at the BAS Research Station at Rothera, the innovative design of which provides a flexible, modular and sustainable laboratory complex (photo credit: Tristan Biggs).


Deep Currents
Surface Currents
Land
Ice shelf
Bathymetry depth (m)
0
250
500
750
1000
Anvers Island
Palmer Station
Adelaide Island
Rothera
Marguerite Bay
Bransfield Strait
Antarctic Peninsula
Larsen Ice Shelf
Alexander Island
65°S
70°S
80°W
70°W
60°W
50°W
km
0
100
200


Warming of atmosphere
Marguerite Bay
Increased glacial discharge
Increased precipitation
Increase in heat flux from deep ocean
Strengthening and veering of winds
Retreat of sea ice and upper ocean warming


Potential Temperature (°C)
Depth (m)
0
50
100
150
1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
Year
1
0
-1
-2
Salinity
Depth (m)
0
50
100
150
1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
Year
34
33
32
Chlorophyll (mg.m-3)
Depth (m)
0
50
100
150
1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
Year
15
10
5
0