SOUTHERN OCEAN OBSERVING SYSTEM

Report Series

Observation Activities in the Ross Sea

Current and Future National Contributions to the Southern Ocean Observing System

SOOS Report Series, #1

Observation Activities in the Ross Sea: Current and Future National Contributions to the Southern Ocean Observing System

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Introduction

This document summarises both known and planned observational programmes in the Ross Sea, with the aim of describing observing activities that contribute to the Southern Ocean Observing System (SOOS). In turn, this will allow the identification of significant gaps that restrict the observation and understanding of future change. The current state of observations in the Ross Sea cannot be considered comprehensive by any standard, but there are significant data sets (particularly for physical oceanography) that can form the basis of an observing system in the Ross Sea.

The most significant gaps in the Ross Sea are the absence of any regular measurements to generate a time series of both biological properties, and sea-ice thickness.

This document does not give geographical specifications on where, within the Ross Sea region, future observations should be made.

Table 1: Summary of activities by nations with stations in the Ross Sea. C = current, P = Planned, AUV = Autonomous Underwater Vehicle, OBS = Ocean Bottom Seismometer, OBH = Ocean Bottom Hydrophone.

Region	Activity	Italy	Korea	NZ	USA
Ice Shelf/ Ice Shelf Cavity	Mooring		P	C/P	
	Aerogeophysics		P		P
	Radar time series		P	P	
	Modelling		P	C	P
	Glider/AUV		P		
Continental Shelf	Mooring	C			P
	Hydrographic sections			C	P
	Sea ice	P		C/P	P
	OBS/OBH		C		
	Glider			P	P
	Seal Observations			C/P	
	Biological			C	P
	Modelling	P		C	P
North of the Continental Shelf	Argo			C	C
	Moorings			P	P
	Hydrographic sections				P
	Modelling			C	P

Outline of the Ross Sea system

Here, the Ross Sea region is considered in its widest sense and includes the ice shelf cavity, the continental shelf, and continental slope and abyssal regions within the Ross Gyre, as there are clear oceanographic connections between these regions. A schematic of the ocean circulation in the two northern regions is shown in Figure 1.

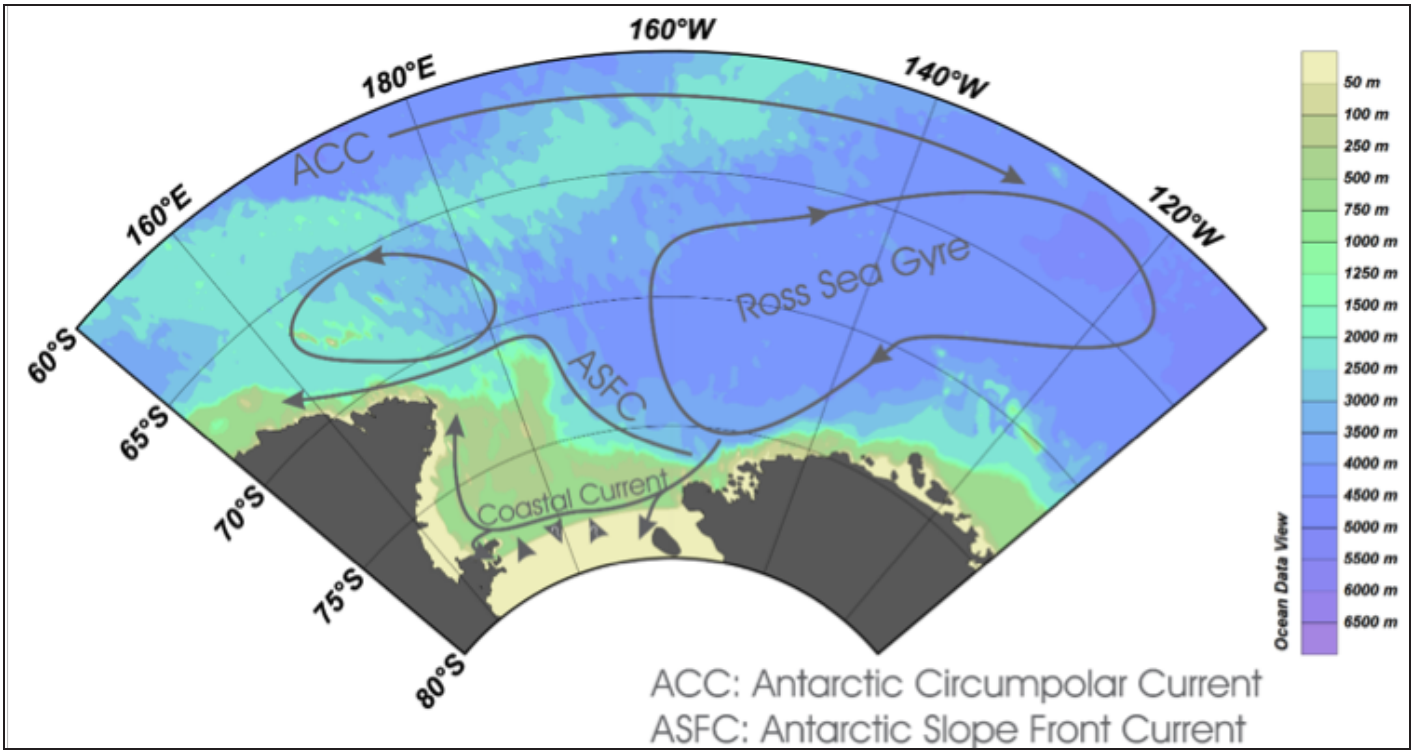

Figure 1: Schematic showing the approximate ocean circulation in the Ross Sea continental shelf and Ross Gyre regions. The arrows along the ice shelf front show areas and direction of cross frontal flow.

The combined cavity beneath the Ross and McMurdo Ice Shelves, has been poorly observed by global standards, but numerical ocean models have provided some insights into the oceanographic processes under the ice shelf (e.g., Dinniman et al., 2011). There have been two sampling sites through the Ross Ice Shelf (Jacobs et al., 1979; Arzeno et al., 2014), while through the McMurdo Ice Shelf there have been more (e.g., Stern et al., 2013; Robinson et al., 2010). On both ice shelves, observations have focused on the physical oceanography of the ocean cavity with geographic coverage limited to the sampling sites. Typically this is due to logistics constraints and the cost of drilling through the ice shelf. A broader suite of observations has been collected along the front of the Ross Ice Shelf, where ship access has allowed a wide range of oceanographic methods to be used to collect a broader range of measurements. These studies have often focused on exchange between the cavity and the continental shelf (e.g., Jacobs et al., 1985).

Away from the ice shelf front, flow within the ice shelf cavity is only known from numerical models, and the flow is highly dependent on the cavity bathymetry and ice shelf draft. Physically the flow is driven by heat fluxes imposed by interaction with the over lying ice shelf. Near the ice shelf front flow is better understood, with recent observations highlighting the role of tides in driving cross front exchange (Arzeno et al., 2014). McMurdo Sound is thought to be seasonally important for inflow to the cavity, and to have persistent outflow of Ice Shelf Water (ISW; water colder than the surface freezing temperature due to interaction with an ice shelf) on its western side (Robinson et al., 2014). However, flow across the front of the Ross Ice Shelf is less clear. ISW has been observed in several sections at depth, but simultaneous velocity measurements have not been available to allow volume transports to be estimated. However, at the whole ice shelf scale Smethie and Jacobs (2005) using temperature, salinity, and CFC measurements along the ice front were able to estimate a net outflow of 0.86 SV for the deep part of the ice shelf, and a transformation time scale of 3.5 years for shelf water to turn into ISW.

The Ross Sea continental shelf is well studied compared to the cavity, and these studies have been drawn together into a number of reviews (e.g., Van Woert et al., 2003; Smith et al., 2012; Smith et al., 2014a). However, observations on the continental shelf remain biased to the western side (Figure 2). The eastern side of the shelf is a challenging environment to undertake marine science due to the heavy ice cover even in summer, the season when most research has been completed.

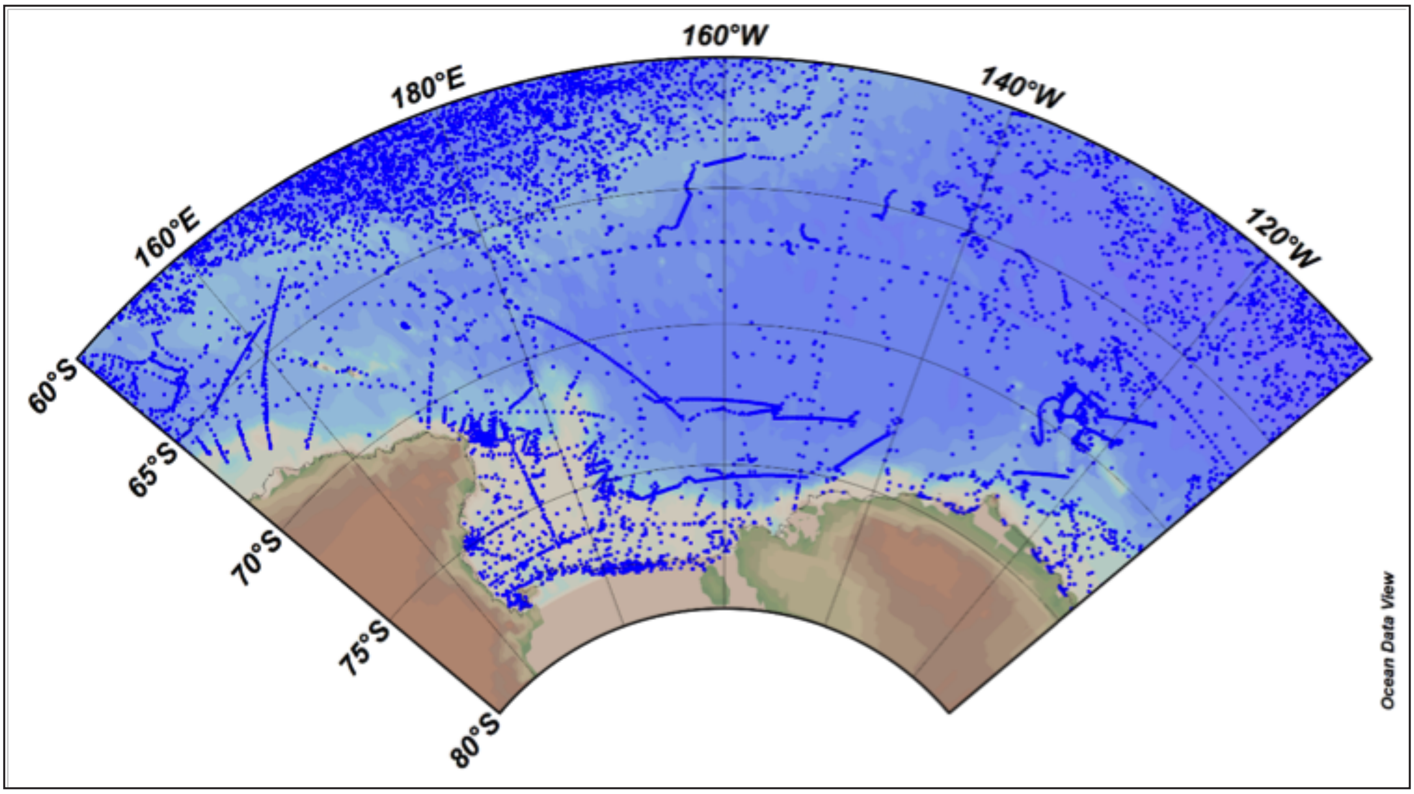

Figure 2: Location of all CTD stations profiles in the Ross Sea stored in the NODC data base (as of 8 December 2014).

On the continental shelf and below the surface layer, flow consists of two anticyclonic gyres connected by a central cyclonic gyre. Most of the circulation on the shelf is barotropic (Pico et al, 1999), except in the vicinity of Ross Island, where numerous baroclinic eddies occur (van Woert et al, 2003). The flow is bounded by a strong narrow coastal current along the front of the Ross Ice Shelf, and along the continental shelf break by the westward flowing Antarctic Slope Front Current (ASFC; also known as the Antarctic Slope Current; Jacobs, 1991). The ASFC is geostrophically driven by a subsurface horizontal temperature gradient between Modified Circumpolar Deep Water (MCDW) and Antarctic Surface Water (AASW), and is coincident with the 0°C isotherm. Although the slope front generates a strong along slope flow, warm MCDW penetrates and introduces warmer waters into the Ross Sea.

The circulation on the continental shelf is extremely sensitive to both changes in the atmospheric circulation and to sea-ice variability (van Woert et al., 2003). Most of the year it is covered by sea ice, which decays in late October and expands during February. Both processes start near the front of the Ross Ice Shelf. Within the sea ice, polynyas are known as sites of strong sea-ice formation and are responsible for significant water-mass modifications due to the high salt flux into the ocean associated with enhanced ice growth. Brine rejected during the ice formation process densifies the water column leading to the formation of cold and saline water masses. These waters spill off the continental shelves into the deep ocean basis affecting the global oceanic circulation. For example, the wind driven Terra Nova Bay (TNB) polynya, persists in the western sector of the Ross Sea throughout most of the winter, so plays a key role in the thermohaline characteristics and circulation of the Ross Sea. Similarly, the Ross Sea Polynya persists throughout the winter near the Ross Ice Shelf at about 180° longitude, and is the site of the major expansion of open water on the continental shelf during spring and summer.

The northern part of the Ross Sea is characterised by an abyssal plain bounded to the south by the continental shelf and to the west and north by the Antarctic-Pacific Ridge. This ridge pushes the Antarctic Circumpolar Current north allowing the cyclonic Ross Gyre to sit between the bathymetric boundaries. To the east the Ross Gyre interconnects with the Antarctic Circumpolar Current (ACC) on its northern side, and with outflow in the coastal and ASFC from the Amundsen-Bellingshausen Sea on its southern side. The gyre is responsible for the inflow of comparatively warm Circumpolar Deep Water (CDW) over most of the water column. Outflowing Antarctic Bottom Water (AABW) is found under the CDW, while at shallower depths AASW, with its properties set by interaction with the atmosphere, is common.

Studies over the last decade in the Ross Sea have provided significant new insights into AABW formation from investigations of source water production and variability to the dynamics of dense outflows. The Ross Sea is an excellent place to study these phenomena because areas with all the relevant characteristics can be relatively easily accessed, and there is now a significant database of hydrographic and tracer data from the Ross Sea continental shelf. These data are sufficient to demonstrate significant temporal variability in properties of the water masses in the southern Ross Sea region from 1960 to 2000, with the High Salinity Shelf Water (HSSW) freshening by > 0.1

during this period (Jacobs et al., 2002). Using a shorter data set acquired at the end of the 1990s, Budillon and Spezie (2000) and Fusco et al. (2009) found a similar rate of freshening in the deep water in the TNB Polynya in the western Ross Sea, where the densest HSSW is formed through intense air/sea interactions. Smethie and Jacobs (2005) also found variability of ISW outflow from the Ross Ice Shelf, based on hydrographic and tracer chemistry data along the Ross Ice Shelf front between 1984 and 2000. Detailed studies in the northwest Ross Sea (Gordon et al., 2009) have also demonstrated the sensitivity of AABW properties and volume flux to processes acting at short time- and space-scales. It is now clear that tidal mixing and advection play critical roles in AABW formation (Whitworth and Orsi, 2006; Muench et al., 2009a; Padman et al., 2009; Wang et al., 2010), while processes associated with small-scale bathymetric features assist the injection of AABW into the deep ocean (Muench et al., 2009b; Padman et al., 2009).

During the last decades AABW has exhibited a freshening and contraction in volume in this area with strong impacts in the Australian sector. The causes of these changes are unknown. Possible explanations in terms of a climate-scale perturbation to the properties of the AABW precursor water masses have been tentatively put forward by a number of authors (e.g., Rintoul, 2007)

Summer observations using fluorometers on moorings (Smith et al., 2011a) showed that while the overall pattern of phytoplankton biomass is consistent with the broad patterns observed by satellites and ship-based investigations (Smith et al., 2014b), there were numerous short-term changes that were likely the result of advection and rapid changes in the depths of the mixed layers. Fluorometers also showed the vertical linkages with vertical flux of organic matter (Smith et al., 2011b) and the importance of short-term loss processes. Analysis of temperature and salinity records indicated that summer conditions began to "erode" (that is, surface temperatures began to cool, and surface salinities began to increase) in mid-January (Smith et al., 2011a), earlier than ship-based observations had suggested. Thus the biological "growing season" is even shorter than had previously been suspected.

Gliders also provide a means by which biological processes can be resolved on space and time scales that cannot be measured by ships. Kaufman et al. (2014) showed that there were very large variations in phytoplankton biomass on short space and time scales, and that it was possible to make broad inferences concerning the composition of phytoplankton from the derived chlorophyll and particulate organic carbon fields. It was noteworthy that large concentrations of phytoplankton biomass were noted at some locations through 200 m, suggesting that rapid vertical flux events occur, which had previously been undetected by sediment traps. Estimates of mixed layers suggest that mixed layers began to increase in mid-January consistent with the mooring results (Smith et al., 2011a). Analysis of glider oxygen concentrations also showed the seasonal productivity patterns, and identified the period of rapid transition from net autotrophy to net heterotrophy during summer (Queste et al., 2014).

Recently, gliders have been used to assess the abundance and vertical distribution of two of the region's critical mid-trophic level components, crystal krill and Antarctic silverfish. These two organisms play central roles within the Ross Sea food web (Pinkerton et al. 2014), as one grazes phytoplankton and in turn is an essential prey item for penguins, seals, fish and whales, while silverfish consume krill and in turn are preyed upon by penguins, fish and seals. Gliders demonstrated the vertical segregation of the two forms within the water column (krill generally were located at approx.. 50 m, while silverfish were located closer to 120 m); furthermore, the temporal and spatial patterns of abundance appeared to be regulated by penguin predation. Phytoplankton abundance varied both in space and time, but given that the region of study was an area approximately 20 x 50 km, the major changes observed were temporal in nature.

Observing Activities

Physical Oceanographic Observations

Currently, physical oceanographic observations are collected using multiple platforms by several countries in the Ross Sea. Here, current observations are described in three geographical regions: the cavity under the Ross Ice Shelf, the continental shelf, and north of the continental shelf.

The Ross Ice Shelf and the adjacent McMurdo Ice Shelf share an oceanographically connected cavity, with the ocean under the McMurdo Ice Shelf recently named Haskell Strait. In the past Haskell Strait and the McMurdo Ice Shelf have been used as either test beds for ice-shelf cavity measurements or have had physical oceanographic measurements collected to serve specific needs, e.g., site survey for the Andrill drilling programme. Currently no ongoing observations have been clearly identified for Haskell Strait or through the McMurdo Ice Shelf.

Under the Ross Ice Shelf, New Zealand (Williams PI) currently maintains a mooring at Coulman High. This is approximately 50 km east of Ross Island, and approximately 7 km back from the front of the Ross Ice Shelf. This mooring was initially deployed in November 2010 for three months along with a second mooring (Arezeno et al., 2014), it was then recovered and redeployed in January 2011 and has been operating since. Data is downloaded at least annually when the mooring is serviced, for access to the data contact Mike Williams (mike.williams@niwa.co.nz). It is likely this mooring will stop operating by the end of 2015. Plans are currently being developed to retrieve and replace the mooring in the future.

Another mooring is currently planned by New Zealand for the mid-Ross Ice Shelf (Hulbe, Stevens PIs). This is scheduled for deployment during the 2016-17 summer season. At a second nearby hole there will also be a series of Conductivity-Temperature-Depth (CTD) profiles and shear measurements. A US tethered Autonomous Underwater Vehicle (AUV) (Schmidt PI) is also expected to be deployed to undertake oceanographic sections under the ice shelf.

The Italian national research programme PNRA (Programma Nazionale di Ricerche in Antartide – National Programme for Antarctic Research; www.pnra.it) has since 1994 deployed a number of oceanographic mooring in the Ross Sea to monitor the oceanographic condition of the shelf waters which are the precursor of AABW and to study biogeochemical cycling. This mooring network has been modified over time in response to changing funding. Currently it consists of 4 moorings located in the western part of the Ross Sea (Figure 3, red dots).

In 2009 all of the moorings, which were previously managed by different Italian research projects, were brought together under a single 5-year monitoring

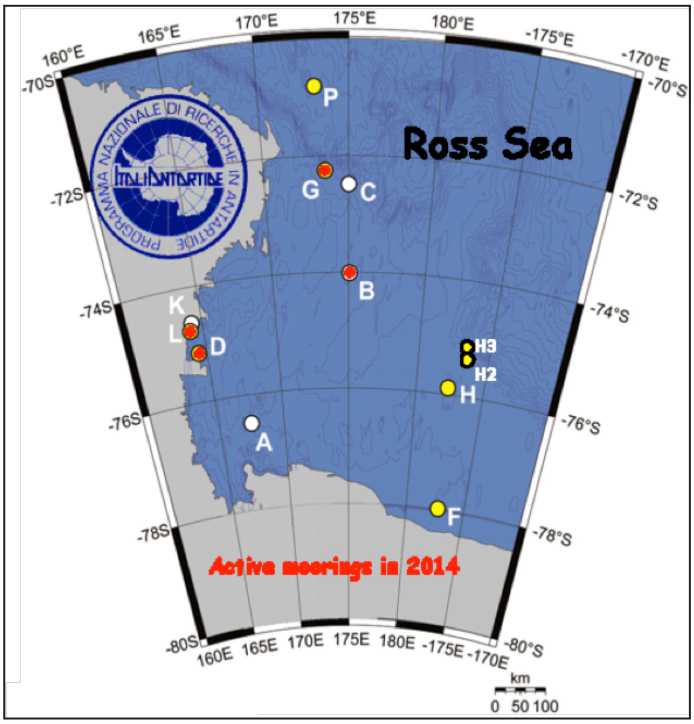

Figure 3: The Italian oceanographic mooring network in the Ross Sea deployed between 1994 and 2014. Red dots indicate mooring that are currently deployed.

programme called "MORSea - Marine Observatory in the Ross Sea" (http://morsea.uniparthenope.it/) under the coordination of the University of Naples "Parthenope".

Currently, the network comprises:

- Mooring "B" located in the Joides Basin operated since 1998 with a focus on biogeochemical fluxes;
- Mooring "D" located in the deepest part of the basin under the Terra Nova Bay polynya, and has been operating since 1995;
- Mooring "L" also located in the Terra Nova Bay polynya and is close to the Italian base "Mario Zucchelli" in the Antarctic Specially Protected Area [ASPA] of Terra Nova Bay;
- Mooring "G" 30 miles far from the shelf break and has been collecting thermohaline and current data since 2003 mainly in the bottom layer occupied by the High salinity Shelf Water, the densest shelf water of the Southern Ocean;

These mooring were last serviced in the 2013-14 season, and are scheduled for service in 2015-16.

In addition to the Italian moorings, New Zealand is planning to deploy three mooring in the Ross Sea in the 2014-15 summer. Two were deployed in December 2014 (Stevens PI) in collaboration with Korea, either side of the Drygalski Ice Tongue. The primary aim of these moorings is to understand flow under the

Drygalski Ice Tongue, and they will be deployed for 2 years. The third mooring (Williams PI) utilises an opportunistic mooring deployment, by augmenting the deployment of an upward looking fisheries echo sounder with current meters and small CTD's. This mooring was deployed in Terra Nova Bay in February 2015 for one year. For the New Zealand moorings to be part of a longer term observing programme requires collaboration with other countries as although NZ mooring equipment is available, regular access to research vessels in the Ross Sea is not.

Sweden (PI Wåhlin) in collaboration with KOPRI is developing plans to deploy an Autonomous Underwater Vehicle (AUV) under the Drygalski Ice Tongue. This is intended as a test of the AUV ahead of a larger programme in the eastern Ross Sea that would conduct a traverse from Thwaites Glacier to the western part of the Getz Ice Shelf in the Amundsen Sea. Although not in the Ross Sea embayment, the Getz Ice Shelf is positioned on the border of the Ross Sea where the Ross Gyre blocks the warm ocean currents from flooding the continental shelf.

Salinity and temperature measurements have also been collected using instrumented seals from sites near Ross Island. Between 2010 and 2012 US researchers (Costa, PI) deployed approximately 60 seal tags. In 2014 Australians researchers (Hindell PI) supported by New Zealand logistics deployed between 10 and 15 tags. There is a desire to extend this into the future as the Australian Integrated Marine Observing System is able to supply tags if logistics support can be found to deploy them.

North of the continental shelf a joint US-Australian-New Zealand-Italian (Speer, Rintoul, Williams, Budillon PIs) Ross Gyre Experiment is being planned to map the circulation and water mass properties of the Ross Gyre. It is in the early stages and still seeking funding. Currently Argo is not measuring within the Ross Gyre as the floats are either not surviving interactions with the sea ice, or not receiving adequate position information under the sea ice. In the Ross Gyre Experiment sound sources will be deployed in February 2017 on fixed moorings to allow sonar position tracking of suitably enabled Argo floats as they circulate in the gyre. Once out from under the sea ice the Argo floats will then return both position and profile data previously collected, as normal. During the mooring deployment hydrographic sections from the abyss across the continental slope and onto the continental shelf will be occupied. This may be augmented by a second series of hydrographic sections using a second research vessel. The observations in this experiment are very dependent on the distribution of Argo floats, the initial deployment of floats are likely to exit the gyre while the sound sources are still working and we are seeking additional opportunities to deploy RAFOS equipped Argo floats in the 2017-18 and 2018-19 seasons.

Up until 2013, 25 transects between New Zealand and the Ross Sea have been occupied by the RV Italica mainly in January and February (Figure 4). These have collected SST, SSS, XBT and XCTD data. This will be continued in the 2014-15 summer, when two Italian scientists will be hosted on board the South Korean RV Araon as part of a collaboration between PNRA and KOPRI (Korea Polar Research Institute). It is hoped this will be continued into the future. The 3 main actions to be undertaken during the 2014-15 season are:

- Collection of in situ temperature data in the layer 0-800m;
- Release of 10 SVP2 surface drifters; and,
- Deployment of 10 ARVOR and PROVOR floats.

Temperature data are usually collected using Sippican T7 probes providing temperature profiles with a vertical resolution of 65 cm and a maximum nominal depth of 760 m. A regular 20 km sampling rate is adopted with increased sampling frequency over the main frontal regions of the ACC. Transects are usually performed in 5 days providing a synoptic picture of the thermal structure of the upper SO in this sector.

Biological Observations

Biological observations are largely limited by the technologies available for continuous measurements. For example, most sensors that provide continuous measurements of biological parameters include optical backscatter (a measure of particulate organic carbon), fluorescence (a measure of chlorophyll and phytoplankton biomass), oxygen concentrations (which can be used to parameterise productivity), and temperature/salinity. Despite the presently limited kinds of sensors, efforts at collection of biological parameters over different timescales have provided considerable insights into our knowledge of biological processes and biogeochemical cycles of the Ross Sea. Given that the next century will have profound changes occurring in the Ross Sea ecosystem (Smith et al. 2014b), obtaining adequate biological observations on the appropriate time and space scales is essential.

Measurements have been collected largely from ships, although gliders and moorings have also been used in the past few years. Sediment traps have been deployed for decades, providing insights into the export of organic matter to depth. Satellites also have provided data on the seasonal shifts of biomass in the ice-free regions of the Ross Sea, and have well characterised the accumulation and removal of phytoplankton on the shelf. Substantial information on higher tropic levels (e.g., seals, penguins, whales) has been collected from land-based studies. Investigation of middle trophic levels (e.g., copepods, krill, and silverfish) have been restricted to a few studies in summer.

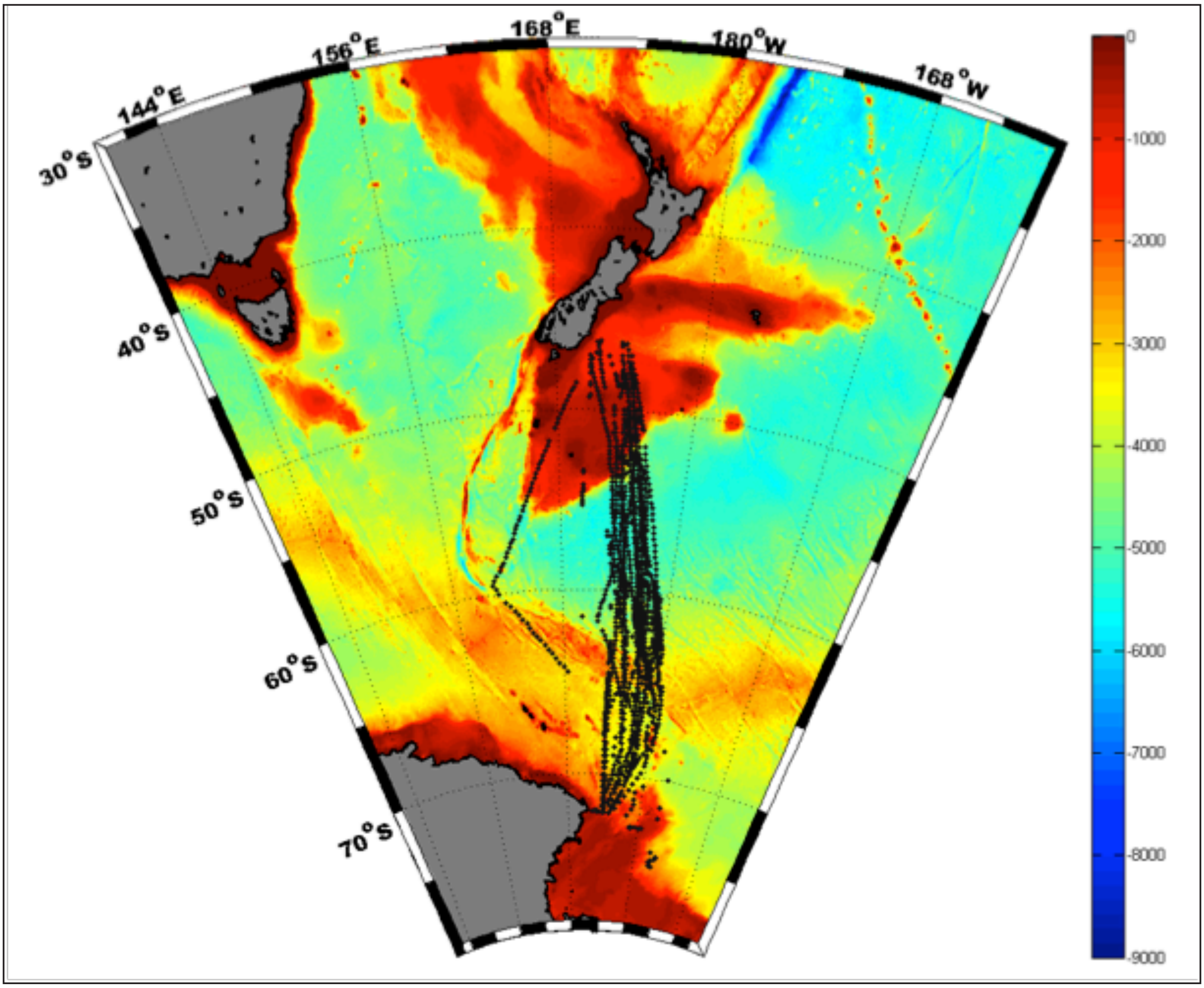

Figure 4. Transects of XBT casts relating to the CLIMA/SOChIC/MORSea programmes (black dots) from 1994 to 2013. Underlying bathymetry (m.b.s.l.) is indicated by color shading.

Geophysical Observations

Ice shelves provide backstress on grounded ice, providing a buffer between the dynamic, changing oceans and the ice sheets. Their role in modulating upstream ice makes surveying their shape, evaluating the nature of the ice-ocean interface, and monitoring potential thinning rates important. Slow-moving airborne platforms (fixed wing or rotary aircraft) are ideal for ice-shelf cavity exploration due to their ability to produce moderately high resolution data along each trackline, their versatility, operational insensitivity to crevasses (compared to surface-based data acquisition), and payload capacity.

Radar sounding is used to measure ice-shelf thickness due to the large dielectric contrast between seawater and ice. Accreted marine ice presents a challenge for many airborne radar systems that do not always penetrate the salty accreted layers. Airborne gravimetry can be used to infer the depth of the water column between the bottom of the ice shelf and the seafloor. Magnetics data combined with seafloor depth control from deployable instruments applied in nearby open water can be used to inform the geological models and thereby improve the resulting bathymetry solutions. Slow acquisition speeds and high quality autopilot systems are important considerations for the airborne platforms while dynamic range and sensitivity should be maximised for the instruments. Baseline instruments for cavity aerogeophysics include profiling and/or scanning or multibeam ice surface altimetry, radio echo sounding for ice thickness, and gravity and magnetics for inversions for seafloor shape beneath the floating ice shelves.

Table 2 summarises the activities proposed and underway to study glacier targets in the Western Ross Sea. Existing data are shown in the right half of the table; 2D profiles are distinct from grids of survey lines. Very few targets in the region have seen enough profiles to form grids of either radar or potential fields, and many targets have only seen a single profile and many of those have only been sampled a single time several years ago. With one exception, planning activities currently only include resources for single or loose collections of 2D profiles.

In addition to the aerogeophysics, fixed radar deployments are planned by New Zealand (Hulbe PI) as part of the mid ice-shelf mooring deployment. This will consist of a single fixed radar, and a mobile second radar to measure gradients in ice-shelf melt. This will be a contribution to the SOOS-endorsed NECKLACE programme (http://www.soos.aq/news/current-news/162-necklace).

Sea-Ice Observations

Sea ice in the Western Ross Sea is known to be increasing, but the processes driving these increases and the implications have not been determined. New and continuing observation campaigns are planned to better understand this sea-ice trend.

A U.S.-lead programme (Ackley lead-PI) entitled, Polynyas, Ice Production & seasonal Evolution in the Ross Sea (PIPERS) plans a multi-platform measurement programme using ship-based measurements (April-May 2017), autonomous buoy arrays (April-October 2017) and airborne surveys (October 2017). This will allow quantification of the full suite of air-sea ice interactions during rapid sea-ice growth, measurement of ice growth and export from polynyas and leads, and ice growth deformation, thickness evolution in pack ice. These will be used to develop better model parameterisations for air-ice-ocean fluxes for both polynyas and ice-covered areas.

New Zealand (Rack and Langhorne PIs) in collaboration with Canadian researchers (Haas) are developing plans and seeking funding and support to fly an electromagnetics induction sounding bird from light aircraft to obtain sea-ice thickness in support of the PIPERS voyage. This would be validated by on-ice observations. If feasible these observations could be repeated in the future.

In McMurdo Sound, contributions will also be made to the Antarctic Fast Ice Network (AFIN; http://seaice.acecrc.org.au/afin/), an international collaboration to make physical and biological measurements on land-fast sea ice stations around Antarctica. This collaboration presently involves Australia, Germany, Japan, China, NZ, and USA. Currently no other long term monitoring of sea ice is planned.

Satellite remote sensing is the most efficient sea-ice observation platform to observe polar regions, due to the very harsh environment that very often hampers conventional in situ measurements and observations. Although nowadays high-quality measurements can be performed using semi-empirical or empirical techniques to generate added value products, those

Table 2: Matrix of planned and currently underway aerogeophysical programmes for targets in the Western Ross Sea sector. The right half of the matrix reflects the existence of profile or gridded ice penetrating radar and potential fields data for each target acquired by previous programmes. Orange boxes represent opportunities for new deployments (no planned or current activities and/or no previous data).

Target Name	Planned	Current	Existing Data			
			Profiles		Grids	
			Radar	Gravity, Mag.	Radar	Gravity, Mag.
Northern McMurdo Ice Shelf	*Profiles*	*Profiles*	✓	✓	✓	✓
Southern McMurdo Ice Shelf	*Profiles*	*Profiles*	✓			
Ross Ice Shelf	*Grids*	*Profiles*	✓	✓		
David Glacier & grounding line	*Profiles*		✓	✓	✓*	
Drygalski Ice Tongue	*Profiles*		✓	✓		
Nansen Ice Shelf			✓	✓		
Mawson, Priestly, Aviator Gl, Ice Tongue	*Profiles*		✓	✓		
Campbell Glacier						
Continental Shelf			N/A		N/A	

techniques present two major drawbacks: they are strictly linked to the specific calibration site and to poor datasets of sea ice on field information. Those drawbacks limit not only the accuracy of the satellite sea-ice estimations but also the chance to use in a synergistic way all the available satellite missions. Upcoming efforts will attempt to improve satellite estimates of thinner sea-ice thicknesses from passive microwave and thicker sea-ice estimates using airborne and satellite altimetry.

In situ measurements will be compared to available products from known algorithm using remote sensed data collected by passive microwave radiometers (SMOS, SSM/I, AMSR-E). This will help to verify satellite products, fill the need for more validation measurements in both hemispheres and further improve the retrieval algorithms as well as the forecast and the analyses of the seasonal sea-ice development.

In particular, observational data will be used to improve the SIT algorithms (Aulicino et al., 2013) for estimating sea-ice thickness in polar regions (optimising its performance for values around 50 cm) and in particular its application to the summer in the Ross Sea. The SIT algorithm is a new empirical procedure developed at Università degli Studi di Napoli Parthenope to estimate sea ice and snow thickness in the Ross and Weddell Seas (Antarctica) using Special Sensor Microwave/Imager (SSM/I) brightness temperatures. This algorithm combines brightness temperature polarization difference and ratio values to obtain sea-ice thickness for seasonal ice up to about 80-90 cm during freezing conditions.

SMOS sea-ice thickness data are derived from the near nadir Level 1C brightness temperatures using a single layer emissivity model and are provided for both Arctic and Antarctic regions by the University of Hamburg. The approximate uncertainties of the SMOS ice thickness retrieval are about 20% for ice thickness less than 30 cm and 100% for ice thickness more than half a meter (upper limit). The greatest benefit of the SMOS data are expected during the cold freeze-up periods when extensive areas of thin sea ice control the ocean-atmosphere heat exchange, which is important for weather and climate, as well as for operational marine applications. To determine changes of the total sea ice thickness and volume it is recommended we use SMOS together with CryoSat-2 data because of their complementary error characteristics.

Deployment of Ice Mass Balance buoys is also planned in PIPERS, which will obtain some baseline thermodynamic (ice growth) ice thickness measurements, from a several month-long time series in a single winter. The buoys will also be in a deformation array to compute the deformation contribution to ice thickness. A significant component of PIPERS is to measure surface elevation (lidar), snow depth (snow radar) and total snow and ice thickness (EMI) over the side from the NB Palmer over longer tracks (10s of kms). Additional correlations will be obtained using correlated surface lidar elevation and under ice AUV (Williams et al 2014) to correlate areal ice thicknesses with areal swaths (several hundred meters square). Both sets of measurements will then be used to develop ice thickness algorithms for converting airborne and satellite altimetry into ice sea ice thickness. The combination of IceBridge (NASA) and planned IcePod (NSF, R. Bell PI) aircraft flights will give a several year time series (Oct 2016-2018 currently) of airborne lidar estimates of sea-ice thickness over the Ross Sea “flux gate” (the 1000m bathymetric contour dividing the Continental Shelf and Deep Basin portions of the Ross Sea). The planned launch of IceSAT-2 in late 2017 will hopefully add a consistent year-round measure of snow surface elevation that, with the surface validation efforts, can be converted to seasonally varying ice thickness measurements. While the IceSAT 2 elevation data will be available for the circumpolar sea-ice zone, the Ross Sea region has the currently planned surface validation study.

Modelling

Models are used to synthesise data and to provide past and future projections of oceanographic and ecological interactions. Many examples of models for the Ross Sea have been published, and many different objectives are addressed by the different models. Advances are being made with data assimilation techniques that will utilise future observations to get higher quality predications. Data assimilation is a mathematical tool for optimally synthesising different types of observations with model initial “guesses” of structuring forcing functions (e.g., forecasts). This procedure will be invaluable in SOOS, as the routine data acquired from moorings, hydrographic surveys, glider surveys, and satellite information can be placed within the context of a full 3-dimensional model to investigate and predict future changes. Use of similar techniques for the entire Southern Ocean will provide a powerful means by which to assess the ongoing changes that are occurring and will occur throughout the region.

Gaps in the Observing System

The current state of observations in the Ross Sea cannot be considered comprehensive by any standard. Gaps identified through this report are listed below:

- No regular hydrographic or repeat CTD measurements on the continental shelf;
- No regular observation in the eastern Ross Sea;
- Sparse Ice Shelf cavity observations;
- Lack of Argo measurements in the Ross Gyre;
- Few biological observations that can contribute to seasonal assessment of the food web;
- No current or planned long-term biological measurements that target the fundamentals of life processes in the ocean;
- Limited geographic coverage of planned sea ice thickness measurements;
- No plans for the regular deployment of gliders for either physical or biophysical;
- Limited winter observations (PIPERS cruise only);
- Large gaps in the bathymetry of the continental shelf remain to filled.

New observation activities in the Ross Sea region have an opportunity to play a significant role in addressing these key gaps. There is also the possibility for involvement in some of the existing planned experiments, such as deploying acoustic tracked Argo floats if the Ross Gyre experiment is funded, making biogeochemical measurements in the New Zealand-supported Ross Ice Shelf project, or contributing to the continuation and/or extension of seal tagging efforts in the Ross Sea.

Appendix 1: Relevant Projects

Investigation of Cryospheric Evolution in the Victoria Land, Antarctica, Won Sang Lee (PI; wonsang@kopri.re.kr)

MORSea: Marine Observatory in the Ross Sea" (http://morsea.uniparthenope.it/)

Vulnerability of the Ross Ice Shelf, Christina Hulbe (PI; christina.hulbe@otago.ac.nz)

Ocean and freshwater forcing of the West Antarctic ice shelves and their grounding zones (Anna Wåhlin (PI; anna.wahlin@gu.se)

NECKLACE: The Network for the Collection of Knowledge on meLt of Antarctic iCe shElves (http://www.soos.aq/news/current-news/162-necklace)

Polynyas, Ice Production & seasonal Evolution in the Ross Sea (PIPERS) Steve Ackley (PI; Stephen.Ackley@utsa.edu)

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