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- An Update

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Observational Activities in the Ross Sea:

Current and Future National Contributions to SOOS

- An Update

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Introduction

The Ross Sea is a critical continental shelf system of the Antarctic, as it is a site of deep-water formation, the most biologically productive region of the Southern Ocean, and harbours massive accumulations of higher trophic levels (Smith et al., 2014). However, significant gaps in our knowledge prevent a clear understanding of the future effects of climate change and other anthropogenic impacts on the oceanography, food web and biogeochemistry of the system. We summarize some of the notable features of the oceanography of the Ross Sea and emphasize recent advances in our understanding, and also highlight present and planned activities by the nations that are heavily engaged in research in the area, especially those that can contribute to a broader observing system. This report is an update and extension of that provided by Williams et al. (2015); activities prior to 2015 can be found in that reference.

The second meeting of the West Antarctic Peninsula and Scotia Arc (WAPSA) Working Group (WG) of the Southern Ocean Observing System (SOOS) was held on July 28th 2020. The meeting was originally planned to be held in Hobart, to coincide with the SCAR 2020 Open Science Conference. However, due to the COVID-19 pandemic, the meeting was held online. We would like to extend our thanks to the Association of Polar Early Career Scientists (APECS) for their assistance with organising the Zoom meeting facilities.

Outline of the Ross Sea system

The Ross Sea region includes the ice shelves and waters beneath it, the continental shelf, and continental slope and abyssal regions within the Ross Gyre, as there are clear oceanographic connections among these regions (Figure 1a,b). All the southernmost sector of the Ross Sea is covered by the Ross Ice Shelf (RIS) which accounts for the 32% of the total Antarctica's Ice Shelf. Estimates of the RIS basal melt rate (Depoorter et al., 2013), indicate a low shelf-wide mean basal melt rates of 0.07 to 0.11 $m\,yr^{-1}$.

The cavities beneath the Ross and McMurdo Ice Shelves have been poorly observed, but numerical ocean models have provided some insights into the oceanographic processes under the ice shelf (e.g., Dinniman et al., 2011, 2018). There have been two sampling sites through the Ross Ice Shelf into waters below (Jacobs et al., 1979; Arzeno et al., 2014), while there have been additional observations through the McMurdo Ice Shelf (e.g., Stern et al., 2013; Robinson et al., 2010). Geographic coverage has been limited due to logistical constraints and the costs of drilling. Basal melting beneath a thin part of the RIS near the Ross Island has been measured using Autonomous Phase-sensitive Radio Echo Sounder (ApRES), which indirectly reflects the circulation near the front (Stewart et al. 2019). A broader suite of observations has been collected along the front of the Ross Ice Shelf, where ship access allows the collection of a broad range of measurements. These studies have often focused on exchanges between the cavity and the continental shelf (e.g., Jacobs et al., 1985) and processes generated by complex air-ice shelf-ocean interactions (Li et al., 2017).

Flow under the ice shelf cavity is largely predicted from numerical models and is highly dependent on the cavity bathymetry and ice shelf draft. It is driven by heat fluxes imposed by interaction with the overlying ice shelf. Near the ice shelf itself, flow is better understood. Recent observations highlighted 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 the melting at depth) on its western side (Robinson et al., 2014). ISW has also been observed near 180oE (Budillon et al. 2011). However, flow across the front of the Ross Ice Shelf remains unquantified. ISW is easily observable at depth, but simultaneous velocity measurements have not been available to allow volume transport estimations. However, along the entire ice shelf Smethie and Jacobs (2005) estimated a net outflow of 0.86 Sv where ice-shelf draft exceeds 300 m, and a time scale of 3.5 years for shelf water to turn into ISW. Solar heating of the surface water in the area close to Ross Island and seasonal inflow of this energy under the North-Western RIS, amplified the basal melt rate in this region (Stewart et al., 2019), demonstrating a more important role of the surface water in the mass ice shelf balance than considered in the past. 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).

The Ross Sea continental shelf is well studied compared to the cavity and most other Southern Ocean's continental shelves (e.g., Smith et al., 2012; Smith et al., 2014a; McGillicuddy et al., 2015). However, observations on the shelf are biased to the western side (Figure 2), as the eastern side is a challenging environment due to the heavy ice cover even in summer, the season when most research is conducted. Silvano et al., (2020) demonstrated that the High Salinity Shelf water (HSSW) salinity rebound (Castagno et al., 2019) observed after 2015 is related to the variability of sea ice originating in the Amundsen-Bellingshausen Sea. In the last two years (2020 and 2021) two oceanographic cruises in the eastern sector of the Ross Sea (carried out within the Italian Antarctic National Program) collected physical and chemical data to characterize the inflow of water coming from the west. The eastern sector of the basin is a crucial area and poorly explored, but will likely be the site of more observational efforts in the future.

On the continental shelf and below the surface layer, flow consists of two anticyclonic gyres connected by a central cyclonic gyre (Smith et al., 2012). Most of the shelf's circulation is barotropic 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 density 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 at depth along the troughs and introduces warmer waters onto the Ross Sea continental shelf (Kusta et al., 2015).

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 begins to decay in late October and expands during February. Seasonal sea-ice reductions 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 associated with enhanced ice growth. Brine rejected during ice formation increases the density of the water column and leads to the formation of cold, saline water masses. These waters flow off the continental shelves into the deep ocean basins, contributing to the global thermohaline circulation. For example, the Terra Nova Bay (TNB) polynya persists in the western sector of the Ross Sea throughout most of the winter and 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 and is the site of the major expansion of open water during spring and summer.

The northern part of the Ross Sea is characterized 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 remain between the bathymetric boundaries. To the east the Ross Gyre interconnects with the Antarctic Circumpolar Current (ACC) that travels close to the continental shelf break of the Amundsen-Bellingshausen Sea. The gyre is responsible for the inflow of comparatively warm Circumpolar Deep Water (CDW). 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. 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. Based on a longer time series (1995-2018), Castagno et al. (2019) found a freshening trend in agreement with the estimated trend (Jacobs et al., 2002, Fusco et al., 2009) until 2014 which was then followed by a quick recovery to HSSW salinities observed in the early1990s. They also noticed coherent increase in some other areas of the Western Ross Sea. In January 2021 the HSSW salinity in TNB was very close to the highest values observed in the past (Falco, pers. comm.)

HSSW is a precursor of the AABW; therefore, changes to its parameters have broad consequences. Studies in the Northwest Ross Sea (Gordon et al., 2009) 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 (Muench et al., 2009a; 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 freshened and contracted in volume with strong impacts in the Australian sector. However, the recent recovery of AABW formation in the Ross has also been observed (Silvano et al. 2020). The causes of these changes have been explored, but remain to be fully elucidated. Possible explanations include a climate-scale perturbation to the properties of the AABW precursor water masses (e.g., Rintoul, 2007).

The Ross Sea shelf is an important CO_2 sink on an annual scale due to its high biological productivity, associated vertical flux rates, intense winds, and high bottom water ventilation rates (Arrigo et al., 2008). The variability of the carbonate system in Ross Sea surface waters (Antarctic surface water - AASW) has been reported at both the large and mesoscale (Mattsdotter et al., 2014; de Jong et al., 2015; Rivaro et al., 2017). Summer observations suggest that the carbonate system is primarily controlled by biological activities (such as primary production). However, the lowest carbonate saturation state (Ω) occurs close to the glacial fronts, suggesting that increasing glacier melt could counteract the effects of primary production because the freshening of surface water, as dilution leads to lower CO_3^{2-}.

Iron biogeochemistry in the Ross Sea has been investigated, with particular attention to dissolved Fe (dFe) (Sedwick et al., 2011; Gerringa et al., 2015, 2020; McGillicuddy et al., 2015; Marsay et al., 2017; Rivaro et al., 2020). Fewer measurements of particulate Fe (pFe) than dFe have been reported (Marsay et al., 2017; Rivaro et al., 2020). Field observations and model simulations suggest four potential sources of dFe in the Ross Sea: Circumpolar Deep Water (CDW) originating from off the shelf and penetrating in troughs at depth; sediments from shallow banks and near shore areas; melting sea ice around the perimeter of polynya; and glacial meltwater from the Ross Ice Shelf (RIS) (Gerringa et al., 2015; McGillicuddy et al., 2015). dFe concentrations were consistently low (<0.1 nM) in surface waters and showed a general increase with depth (Sedwick et al., 2011; Marsay et al., 2017). The samples collected in coastal waters at Terra Nova Polynya had dFe concentrations significantly higher than those measured in open waters (Rivaro et al., 2020), possibly due to enhanced atmospheric inputs within katabatic winds. Atmospheric inputs are restricted spatially, but are significant in a small area in the southern Ross Sea that receives wind input from the Dry Valleys (de Jong et al., 2013). Vitamin B12 limitation has also been reported at a few locations (Bertrand et al., 2007) and a mutualistic interaction between bacteria and diatoms suggested as being significant in terms of Vitamin B12 supply.

dFe availability can limit primary production and influence phytoplankton composition. dFe-binding organic ligands play an important ecological role because they can increase the residence time of Fe. The absence of vertical variability of the Fe-binding dissolved organic ligands indicates that the ligand groups were not labile and might be transported into the Circumpolar Current. Coastward stations of TNB also had particularly stable complexes of Fe and natural ligands (Rivaro et al., 2020), although the origin of these ligands is uncertain

The spatial and temporal mosaic of phytoplankton dynamics in the Ross Sea is complex, as there are significant inter-annual variations (Smith et al., 2011a; Mangoni et al., 2017), but the general pattern is relatively consistent, although the phenology may not be. That is, early blooms are dominated by the haptophyte Phaeocystis antarctica in colonial form, and upon severe iron limitation, it disappears and is replaced by active growth of diatoms (Smith et al., 2014). Additional functional groups are occasionally observed (e.g., dinoflagellates near Cape Adare; choanoflagellates in the central Ross Sea; cryptophytes near glacial inputs; Bolinesi et al., 2020), but the overwhelming dominance of the two functions groups – haptophytes and diatoms – remains central to the food web and biogeochemical cycles. An imbalance between phytoplankton standing stocks and primary consumers appears to exist, although few studies on grazing loss rates and distributions are available. Hence, the quantitative impact of zooplankton grazing in the Ross Sea can only be inferred from sediment trap collections, which suggest that losses due to fecal export are minimal except for late summer (Smith et al., 2011a).

Summer observations using moored fluorometers 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 (Smith et al., 2011a). 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" may be even shorter than had previously been suspected. De Jong et al. (2017) found evidence of late summer biomass accumulations within freezing ice fields in Terra Nova Bay as part of the TRACERS program and suggested that this accumulation had not been detected previously due to the late occurrence in fall. However, such accumulations also could have been passively induced by rising frazil ice crystals as suggested years ago (Ackley and Sullivan, 1994). Seasonally integrated carbon export below 200 m was ca. two-times higher in diatom-dominated Terra Nova Bay compared to the Phaeocystis antarctica-dominated central Ross Sea (de Jong et al., 2017).

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 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 on short time scales; these have not been detected by sediment traps. Estimates of mixed layers suggest that mixed layers began to increase in mid-January (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., 2015).

Using both glider and climatologies derived from historical ship observations, Smith and Kaufman (2018) concluded that the seasonal progression of phytoplankton was bimodal – that is the spring bloom that is observed by enhanced chlorophyll concentrations occurs from late October through the end of December and is driven by growth of the haptophyte Phaeocystis antarctica. A second bloom that is characterized by low chlorophyll concentrations but high particulate organic carbon (POC) levels is dominated by diatoms. The high POC/chl ratios result from acclimation to limiting iron concentrations (Sedwick et al., 2011), and allow growth to be maintained during periods of extremely low iron levels. Glider studies using a reassessment of fluorescence patterns confirmed this pattern of growth and the nature of iron limitation (Ryan-Keogh and Smith, 2021).

Satellite estimates of phytoplankton biomass in the Ross Sea have been used extensively to drive bio-optical models of primary production (e.g., Arrigo et al., 2003; Schine et al., 2015). However, such models utilize constant POC/chl ratios. Using a variable POC/chl ratio based on climatological means, Smith and Kaufman (2018) showed that primary productivity is substantially underestimated, and suggested that annual production was on average 72% greater than bio-optical models suggest. Furthermore, a reassessment of the accuracy of routine NASA algorithms in the Ross Sea showed that both chlorophyll and POC estimates are highly biased and underestimate observed values (Chen et al., 2021). Impacts of these underestimates on food webs and biogeochemical cycles need to be re-analysed in the coming years, but it is clear that rates of production need to be fully re-assessed.

Gliders have also 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 (Ainley et al., 2015). These two organisms play central roles within the Ross Sea food web (Pinkerton et al. 2014), as krill graze phyto- and zooplankton and in turn are essential prey items for penguins, seals, fish and whales, while silverfish consume krill and copepods, 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 ca. 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 (Ainley et al., 2015). Phytoplankton abundance varied both in space and time, but given that the study region was approximately 20 x 50 km, the major changes observed were temporal in nature (Jones and Smith, 2017).

In the southern Ross Sea, as a part of the Inter-annual Variability in the Antarctic–Ross Sea (IVARS) program, sediment traps were deployed during the austral summers of four years: 2001/02, 2003/04, 2004/05, and 2005/06 (Smith et al., 2011b). Sediment traps were also deployed in the Southwestern region of the Ross Sea polynya in 2005/06 and 2008/09 for a year as part of the Italian Long-Term Ecological Research network (LTER-Italy). High sinking particle fluxes during the summer and early autumn were not coincident with the algal bloom, but seemed be to temporally disconnected from phytoplankton biomass and growth and affected by the variations in the sea ice extension, lateral advection, re-suspension, and the Iceberg B-15. A marine snow imaging system was also deployed in the southern Ross Sea to understand of the mechanisms and rates of carbon export from the euphotic layer as a part of the IVARS program. Asper and Smith (2019) estimated that the contribution of aggregates to the total POC was ca. 20% over the entire water column, and suggested that new approaches to quantifying the abundance and carbon contributions of aggregates of their role in the biological carbon pump system.

The Ross Sea has abundant air-breathing, marine predators and supports 25% of the world's emperor penguins (Fretwell et al. 2012), 40% of the world's Adélie penguins (Lynch and LaRue 2014), and 40% of all reproductive, female Weddell seals (LaRue et al. 2021). Population trends for these species are difficult to obtain given the size of the Ross Sea and the inaccessible nature of their habitats (e.g., fast ice). However, annual aerial surveys of emperor penguins in the austral spring revealed a high degree of variability in population size and in adult:chick ratios (Kooyman and Ponganis 2017), although the metapopulation of 7 colonies appears to be stable. The southern-most colony in the Ross Sea at Cape Crozier has been increasing since the B-15 iceberg dislodged (now approximately 1,000 breeding pairs); the largest colony in the world at Coulman Island hosts ~25,000 breeding pairs, but can vary widely among seasons (Kooyman and Ponganis 2017). Emperor penguins can dive to 500 m and hold their breath for >30 minutes; their diet in general consists of crustaceans and fish.

Determining trends for Adélie penguins in the Ross Sea has also been challenging. Adélie penguins show negative geographic structuring of colony locations (Santora et al. 2020) and tend to be associated with large, productive polynyas. The southern Ross Sea metapopulation of Adélie penguins have been studied for >35 years, which has resulted in a greatly improved understanding of population dynamics, foraging, diet, habitat, and behaviours. Antarctic silverfish is a critical prey item for Adélie penguin chicks on Ross Island (Lyver et al. 2014), although there is evidence of switching to krill as primary prey in the summer (Ainley et al. 1998). Population dynamics are driven by different factors depending on location (e.g., skua predation at Cape Royds vs. density-dependence at Cape Crozier; Schmidt et al. 2021).

Weddell seals have been intensively studied (e.g., at Erebus Bay; Rotella et al. 2012). In the Ross Sea Weddell seals are situated farther from Adélie penguin colonies and near small emperor penguin colonies (LaRue et al. 2019), and are associated with tidal cracks near deep water. As of 2011, the population of breeding female Weddell seals was estimated to be ~84,000 individuals, but LaRue et al. (2021) noted that there is evidence of declines in the northern section of the Ross Sea over the past 50 years despite ice conditions remaining constant and recovery from historic declines due to harvesting. Weddell seals prey on Antarctic silverfish and recent evidence suggests they can be benthic foragers, at least near McMurdo Sound (Harcourt et al. 2021) and diet can vary widely (Foster et al, in prep). Their ability to obtain prey also varies seasonally with chlorophyll concentrations in the surface layer, as they are visual predators (Beltran et al., 2021).

Observing Activities

Physical Oceanographic Observations

Currently, physical oceanographic observations are collected using multiple platforms by several countries in the Ross Sea. In 2009 all the moorings that were previously managed by different Italian research projects were brought together under a single monitoring 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 and close to the Italian base Mario Zucchelli;
- Mooring G: 30 miles from the shelf break has been collecting data since 2003, mainly in the bottom layer occupied by the High Salinity Shelf Water. In 2014 the mooring was extended to 200 m to collect data from CDW intrusions. Technical failures prevented the mooring recovery, and no data are available for the period 2016-2021. It will be re-deployed during the austral summer 2021-2022.

The MORSEa project has included the release of drifters and floats during each transect from New Zealand to the Ross Sea to increase the number of drifters and floats deployed in this sector of the Southern Ocean. About 50 floats and drifters (see http://maos.inogs.it/#/data) were deployed in the ACC. Some Argo Floats were deployed along the RIS and in TNB in stay-on-the-ground mode, to collect data while approximately holding position (Figure 3). This approach allows collection of data in winter during ice-covered periods. Porter et al. (2019) used Argo floats data collected using this approach to study the seasonal evolution of the mixed layer.

Through 2015, 25 transects between New Zealand and the Ross Sea have been occupied by the RV Italica in January and February. Two more transects were carried out on 2020 and 2021 during the first and second oceanographic cruise of the new Italian ice breaker Laura Bassi. Along each transect, SST, SSS, XBT and XCTD data (in few cases) were collected. One more XBT transect was collected on February 2017 thanks to the cooperation with the KOPRI, when four Italian scientists were hosted on board of the RV Araon. However, only one additional survey as completed in 2020 on this transect, with CTDs and acoustic surveys.

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 limited kinds of sensors, efforts at collection of biological parameters over different time-scales 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, marine mammals and moorings have also been used in the past few years. Satellites also have provided data on the seasonal shifts of biomass in the ice-free regions of the Ross Sea, and have characterized 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, and future efforts will include satellite assessments of whales. Investigation of middle trophic levels (e.g., copepods, krill, and silverfish) have been restricted to a few studies in summer (Smith et al. 2017).

Geophysical Observations

Ice shelves provide back stress 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 track, 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 sea floor. 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 maximized for the instruments. Baseline instruments for cavity characteristics include profiling and/or scanning or multi beam ice surface altimetry, radio echo sounding for ice thickness, and gravity and magnetics for inversions for seafloor shape beneath the floating ice shelves.

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.

In McMurdo Sound, contributions will also be made to the Antarctic Fast Ice Network (AFIN; http://seaice.acecrc.org.au/afin/), an international collaboration of 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 high-quality measurements can be performed using semi-empirical or empirical techniques to generate added value products, those techniques present two major drawbacks: they are strictly linked to the specific calibration site and to poor data sets 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 thickness from passive microwave and thicker sea-ice and snow thickness estimates using airborne and satellite altimetry.

In situ measurements will be compared to available products from known algorithms 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 for estimating sea-ice thickness in polar regions (optimizing 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.

A field effort during austral autumn, 2017 was conducted, with the purposes being to quantify the sea-ice production rates in autumn (the period of maximum sea-ice extension) and its drivers, as well as to assess the impact of sea-ice production on water mass characteristics, and in particular High Salinity Shelf Water (Ackley et al., 2020). Although the autumn freeze period that year was delayed by some two months, winter sea ice production was not anomalous. Ice thickness in the central pack was modest, with a model value of < 0.4 m and snow thickness of <0.1 m (project data available at http://www.usap-dc.org/view/project/p0010032). Analysis of a katabatic wind event at Tera Nova Bay suggested that the wind speeds were 35 m s-1 near land and decreased to 18 m s-1 99 km offshore (Guest, in press). Depths of the winds were estimated to be ca. 700 m. The winds drove extreme heat loss rates from the ocean to the atmosphere, copious ice formation rates, and distributed frazil ice through the upper 10 m of the water column (Ackley et al., 2020).

Numerical Models

As an important component in the global climate system, the coupled atmosphere-ocean-ice system in the Ross Sea has to be simulated in coupled global climate models or earth system models. Unfortunately, the inter-model spreads for the Ross Sea circulation and water mass properties are large in these models (Wang and Meredith 2008; Wang 2013), presumably owing to their coarse resolutions and model drifts induced by inaccurate process representations. Also, these models have poor ability to simulate the processes in the Antarctic marginal seas, including the continental shelf of the Ross Sea. Forced by atmospheric reanalysis data, stand-alone global ocean-sea ice models have been employed to simulate the circulation and water mass transformation in the Ross Sea, although the climate drifts resulted from inaccurate descriptions of interactions between atmosphere and ocean can be suppressed in these models, the model drifts still exist, as a result from some internal oceanic processes cannot be properly represented. It is particularly difficult to capture the processes related to the bottom water formation in the marginal seas around the Antarctic, which inevitably leads to large drifts in bottom water properties in global stand-alone ocean-sea ice models, such as NEMO (Hieronymus and Nycander 2013) and MITgcm-ECCO$_2$ (Wang et al. 2017).

To reduce the drifts, data assimilation techniques that utilize observations are valuable. Data assimilation is a mathematical tool for optimally synthesizing different types of observations with model initial "guesses" of structuring forcing functions (e.g., forecasts). This procedure has been applied in SOSE (Marzloff et al. 2010), with the routine data acquired from moorings, hydrographic surveys, glider surveys, and satellite information being assimilated into a full 3-dimensional ocean-sea ice model. This approach provides a powerful means by which to assess the ongoing changes that are occurring and will occur throughout the region. It has also been used in a bio-physical model of plankton from the southern Ross Sea in which glider data were assimilated (Kaufman et al., 2017).

Another approach for improving simulations of the Ross Sea circulation is using high resolution regional models. In these models with limited domains and hence reduced computing cost, the model resolutions are much higher than those global models and more critical processes can be better resolved. Regional modeling studies have coupled Regional Ocean Modeling System (ROMS) to a static thermodynamic ice shelf module, either with a prescribed salt flux associated with sea ice (Jendersie et al. 2018) or with a dynamic sea ice model (Dinniman et al. 2018). To resolve oceanic eddies, Mack et al. (2019) further increased the model resolution to 1.5 km, in contrast to the typical grid sizes of 5 km (Jendersie et al. 2018; Dinniman et al. 2018). As suggested by Mack et al. (2019), to fully resolve eddies near the site of deep convection in the continental shelf, the model grid size needs to be further reduced.

ROMS is a free-surface, terrain-following, primitive equations ocean model. Models with different vertical coordinates may also need to be applied in the Ross Sea, as in other marginal seas (Nakayama et al. 2014; Liu et al. 2017, 2018). By conducting inter-model comparisons among models with different configurations, critical processes can be better understood and more faithfully simulated. MITgcm, a z-coordinate model, has been used to develop a high resolution (grid size of 1.5 km) regional coupled ocean-sea ice-ice shelf model in the Ross Sea (L. Yan et al., personal communication). Future efforts should also be devoted to

i) improving bathymetry and ice shelf draft;

ii) developing parametrisations of sub-grid processes; and

iii) employing idealized models with various resolutions from resolving sub-mesoscale eddies to resolving turbulence.

Gaps in the Observing System

The current state of observations in the Ross Sea cannot be considered comprehensive. Some gaps identified are listed below and in Table 1:

- No regular hydrographic measurements on the continental shelf, at the shelf break and on the slope where the bottom waters form and cascade;
- Few routine observations in the eastern Ross Sea;
- Sparse ice shelf cavity observations;
- Few Argo measurements in the Ross Sea continental shelf and gyre;
- Lack of continuous observations (moorings) in some areas (RIS, Eastern Ross Sea and Glomar Challenger mouth) as well as other crucial regions;
- Few biological observations that contribute to seasonal assessment of the food web, particularly in the areas designated as a Marine Protected Area by CCAMLR;
- Limited geographic coverage of sea ice thickness measurements;
- No plans for the regular deployment of gliders for either physical or biophysical observations;
- Severely limited winter observations at a spatial scale large enough to adequately support modeling efforts.

New observation activities in the Ross Sea region have an opportunity to play a significant role in addressing these key gaps. It is hoped that in the near future a more comprehensive understanding of the oceanographic processes operating in the Ross Sea emerges and greatly improves our understanding of the complex physical-biological interactions and their impacts on biogeochemical cycles emerges, as well as providing a coherent view of the changes in the future Ross Sea

Relevant Projects

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

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

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

Polynyas in Coastal Antarctica (PICA): Linking Physical Dynamics to Biological Variability; PIs: Weifeng (Gordon) Zhang wzhang@whoi.edu; Rubao Ji, Stephanie Jenouvrier, Ted Maksym (WHOI) and Yun Li (UDel)

Effect of the eaSTern inflow of water on the ROss Sea salinity field variability (ESTRO), PNRA18/ 00258.B1 still ongoing (PI Enrico Zambianchi, enrico.zambianchi@uniparthenope.it)

PhySIcal and bioGeochemical traciNg of wATer masses at source areas and export gates in the Ross Sea and impact on the SoUtheRn OcEan (SIGNATURE), PNRA/19_00116, activity scheduled in the austral summer 2022-2023 (P.I. Pierpaolo Falco pierpaolo.falco@univpm.it)

SOLOMON: Southern Ocean Long-term Observation & MONitoring (PI Jisoo Park jspark@kopri.re.kr) (2020~2025)

P2P: Predators to Plankton — Biophysical Controls in Antarctic Polynyas (PIs David Ainley dainley@penguinscience.com; Grant Ballard, Walker Smith, Karen Heywood)

CDW Effects on glaciaL mElting and on Bulk of Fe in the Western Ross sea (CELEBeR) (PI Paola Rivaro paola.rivaro@unige.it)

Biodiversita' E Funzionamento Degli Ecosistemi Planctonici Del Mare Di Ross Nell"Oceano Meridionale in Cambiamento (P-ROSE) (PI Olga Mangoni olga.mangoni@unina.it)

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Table 1: Summary of activities by nations with stations in the Ross Sea (IT = Italy; RoK = Republic of Korea; PRC = People's Republic of China; NZ = New Zealand; USA = United States of America). C= current, P= Planned,; AUV = Autonomous Underwater Vehicle.

Region	**Activity**	**IT**	**RoK**	**PRC**	**NZ**	**USA**
Ice Shelf/ Ice Shelf Cavity	*Moorings*	*C*	*C*		*C*	
	Modeling	*C*		*C*	*C*	*C*
	Glider/AUV					*C*
Continental Shelf	*Moorings*	*C*	*C*		*C*	
	Hydrographic stations	*C*	*C*	*C*		*C*
	Sea ice					*P*
	Glider					*C*
	Higher trophic level observations			*C*		*C*
	Biological observations	*C*	*C*	*C*		*C*
	Modeling			*C*		*C*
	ARGO	*C*				*C*
North of the Continental Shelf	*ARGO*	*C*				*C*
	Moorings					
	Hydrographic observations	*C*	*C*	*C*		*P*
	Biological observations	*C*	*C*	*C*		*P*
	Modeling	*C*	*C*	*C*		*C*

Figure 1a: 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. From Williams et al. (2015).

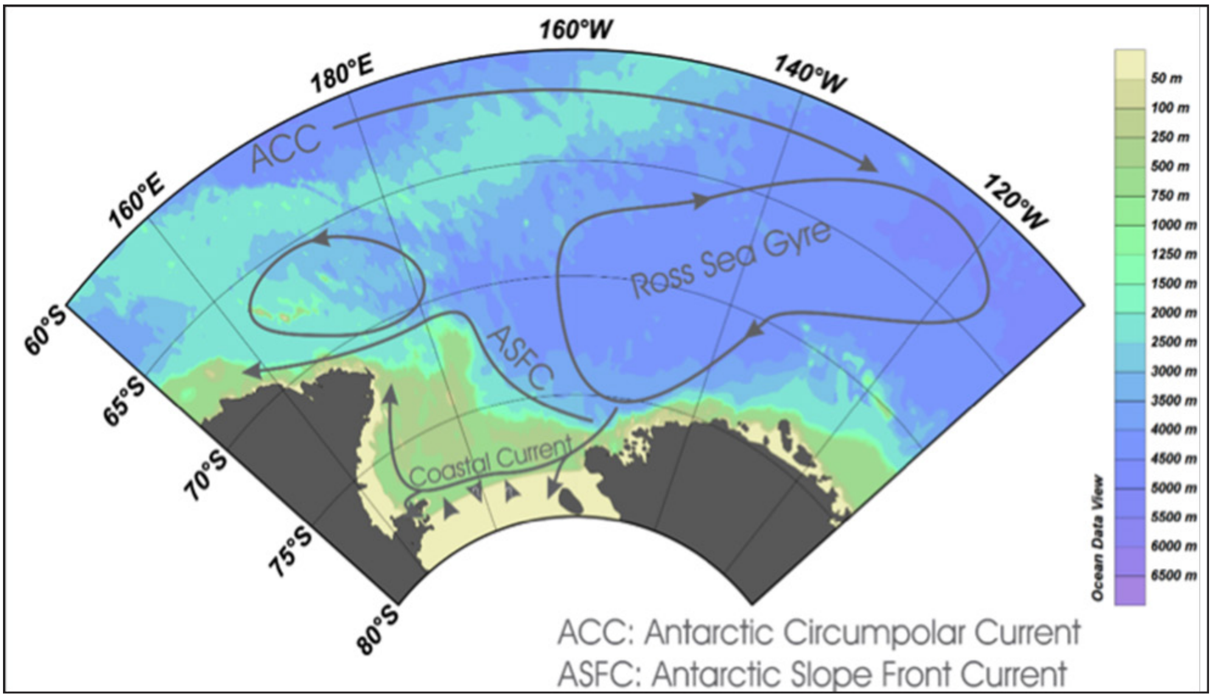


Figure 1b. Diagram of surface circulation in the Ross Sea, including the sites of exchanges with waters under the ice shelf (from Sedwick et al., 2011).

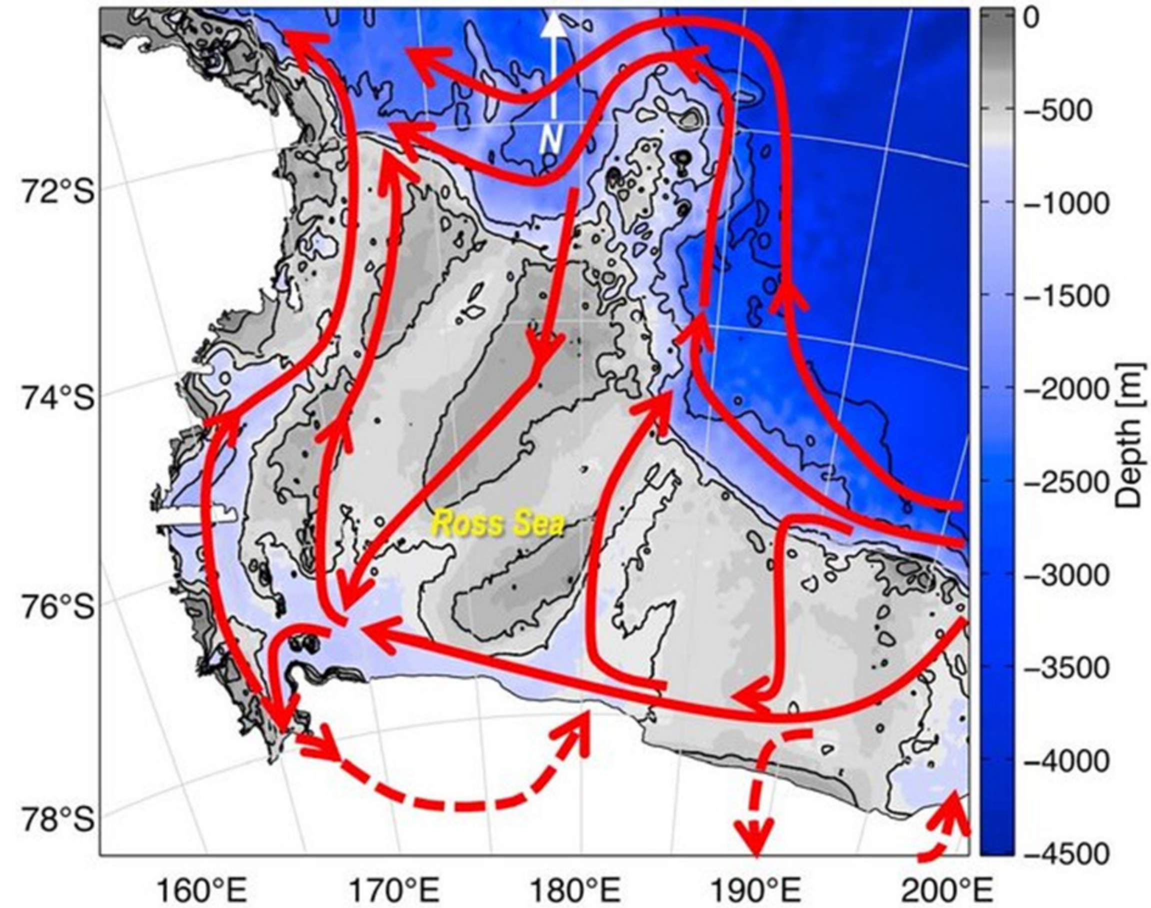


Figure 2: Location of all CTD stations profiles in the Ross Sea stored in the NODC data base (as of 30 September 2021).

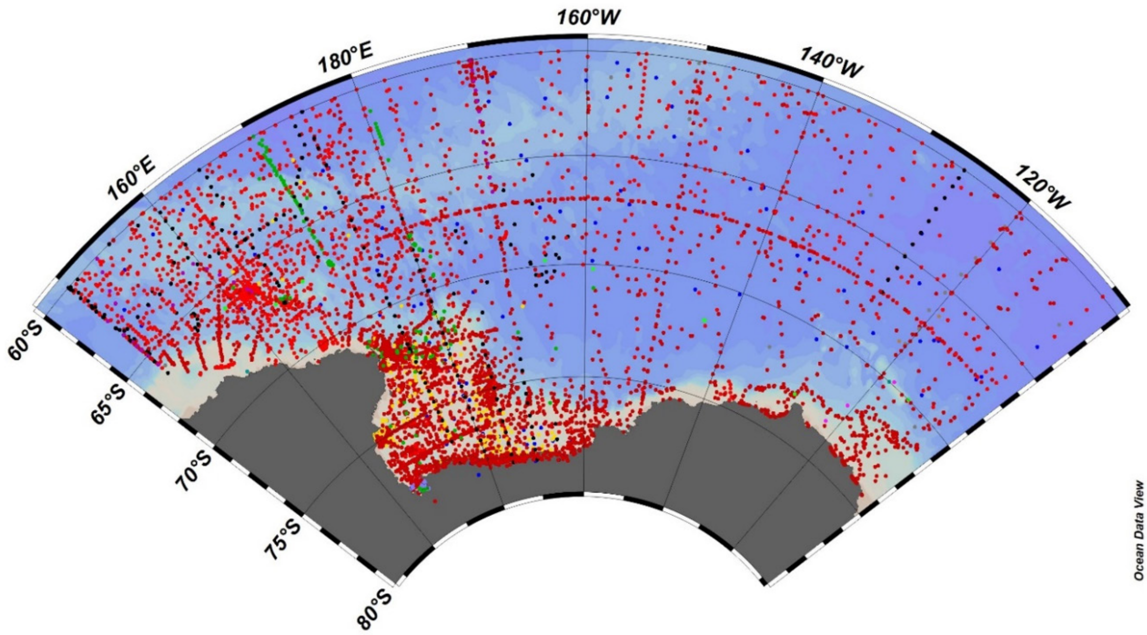
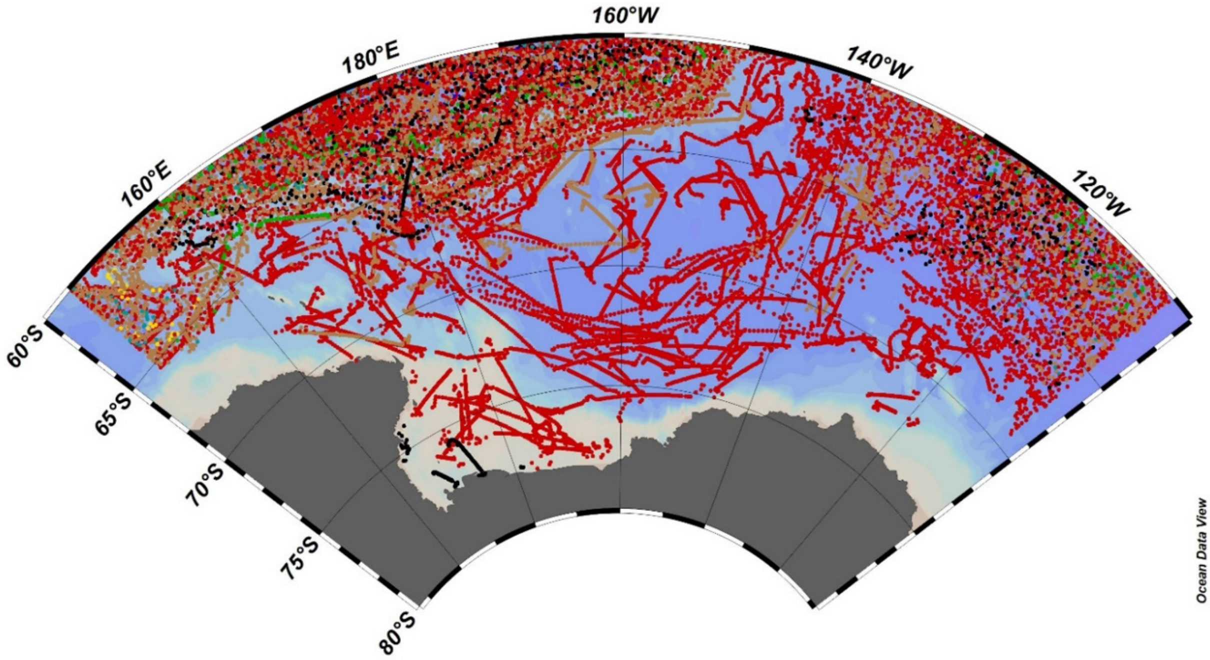


Figure 3: Map representing all of the Argo-floats deployed before September the 30, 2021 between 60 – 80°S and 150°W-130°E. The colors indicate the different national programs contributing to Argo-float deployments.



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SOUTHERN OCEAN
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