SOUTHERN OCEAN OBSERVING SYSTEM

Report Series

# Report on the 2017 Ross Sea Working Group Meeting

SOOS Report Series, #6

2017

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## Citation

Smith, W., Williams, M., Zhou, M., and Budillon, G, (2017). Report on the 2017 Ross Sea Working Group Meeting. *SOOS Report Series, #6*. Zenodo.

## Summary

The Ross Sea is an important sector of the Southern Ocean and a necessary focus of the Southern Ocean Observing System (SOOS). The first SOOS Ross Sea Working Group workshop was held to identify the current and planned observations in the Ross Sea, and other nearby areas which are scientifically important to observe to understand the Ross Sea. These include the polynyas, boundary regions of the Ross Sea, the under sampled eastern Ross Sea, and the Ross Gyre. While a single comprehensive observing system would be ideal, hypothesis driven research is more likely to contribute components to an observing system, thus free and open international exchange of data will be required to achieve integration between observing system components.

The Marine Protected Area in the Ross Sea and the associated Research and Monitoring Plan of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) provide a collaborative opportunity to support an ocean observing system in the Ross Sea, and collaborations between SOOS and CCAMLR should be continued and expanded.

Recommendations from the workshop include the need 1) to observe at all temporal and spatial scales in the Ross Sea, and 2) to understand the linkages among physical processes, biogeochemical cycles, and biological processes. These objectives should provide the data to assess the expected changes and change rates, in order to provide credible projections for future states in the Ross Sea.

## Introduction:

The Ross Sea sector of the Southern Ocean is a critical region to the oceanography of the global ocean, being the site of significant deep-water formation, a rapidly changing region, and home to a highly productive ecosystem. Changes in its physical features have been observed for decades, and are expected to continue in future. As such, coordinated observations of these changes are critical to enable an understanding of potential impacts, as well as to underpin projections of oceanographic and ecological modifications that will occur in the coming decades. The Southern Ocean Observing System (SOOS) is an international initiate with the mission to enhance observations of the Southern Ocean. Towards this end, SOOS has developed a focused Ross Sea Regional Working Group (WG) to identify and deliver new and historical data, and to foster international efforts to monitor changes in the Ross Sea sector.

The Ross Sea WG held a meeting in September 2017 which was designed as a first step to enhance efforts in our understanding of the Ross Sea and its multiple interactions among the atmosphere, ocean, ice and biogeochemistry. The meeting was held in Shanghai, China and sponsored by the following: Institute of Oceanography, Shanghai Jiao Tong University; Ocean Carbon and Biogeochemistry Office, Woods Hole, MA, USA; Southern Ocean Observing System Office, Hobart, Australia; Second Institute of Oceanography, Hangzhou,

China; and the National Laboratory for Marine Science and Technology, Qingdao, China (Appendix 1). The financial support of all is gratefully acknowledged.

## Overview of the Ross Sea:

The Ross Sea sector of the Southern Ocean extends from approximately 160°E to 120°W and from the southern extreme of the Ross Ice Shelf to 50°S, and hence encompasses the continental shelf (depths less than 750 m) and slope, and the deeper portions of the southern Pacific (and its associated sea mounts and islands; Figure 1 and 2). The terrestrial portion of the Ross Sea is largely ice covered and is the site of a number of major research stations such as Scott Base (NZ), McMurdo Station (US), Mario Zucchelli Station (IT) and Jang Bogo Station (Korea). Furthermore, China has plans to build a new base in the coming years as well. Given these logistical bases, the Ross Sea has been the site of considerable research activity in the past, and will continue to be a focus of research in the future.from other countries engaged in Antarctic research (not represented at this meeting), other SOOS WGs, and people from other SCAR disciplines (especially glaciologists, terrestrial biogeochemists, atmospheric scientists and palaeoclimatologists). Alternative routes to funding were also discussed at length, including engagement with industry and citizen science, including work with cruise ships and the development of user-friendly apps.

The Ross Sea sector has been scientifically investigated since the initiation of Antarctic exploration in the early 1900's. Permanent bases were established during the International Geophysical Year in 1958, and the region developed into a base for support of land/ice science observations for the entire continent. Aspects of the oceanography and ecology are very well known relative to other areas in the Southern Ocean, allowing for increasingly sophisticated research to be conducted. The Southern Ocean is exceptionally important to global processes; for example,

- It is the single most important site for removal of atmospheric heat. Specifically, 93% of the total heat energy has been removed by the ocean, and 75% of this has entered the Southern Ocean.
- 30% of anthropogenic $CO_2$ emissions have been absorbed by the ocean, and 40% of this by the Southern Ocean.
- A 2% drop in ocean oxygen levels in the past century has occurred as a result of slowing circulation, with ~50% of this change supplied from the Southern Ocean.

The Ross Sea contributes substantially to all of these changes. In addition, the Ross Sea continental shelf has been estimated to be responsible for 28% of the total removal of anthropogenic $CO_2$ in the Southern Ocean (Arrigo et al. 2008), which emphasizes the extreme importance of the region to processes in the entire ocean.

Ice concentrations have been shown to be significantly increasing in the Ross Sea sector (Stammerjohn et al. 2012), and the Ross Sea has been described as the “driver” for changes in the entire Southern Ocean ice concentrations. That is, while the Amundsen-Bellingshausen sector (ABS) has shown decreased concentrations of ice since 1979, the Ross Sea sector has shown even greater increases. Both appear to be driven by changes in the location of atmospheric pressure systems, which provide heat from the north (in the case of the ABS sector) and cool temperatures from the continent (in the case of the Ross Sea). Regardless, these changes in ice have been a significant feature of the Ross Sea and the Southern Ocean as a whole.

The region is known to be the site of formation of High Salinity Shelf Water along the coast of Victoria Land during winter. This water flows northward in topographic depressions and off the coast to join the oceanic thermohaline circulation. Exchanges between the continental shelf and slope are very energetic, and likely include substantial fluxes of nutrients and biogenic matter as well. The area also likely is important for food web processes, as it is the site of substantial foraging activity by penguins and has substantial concentrations of Antarctic krill. The shelf break is also the site of concentrations of Antarctic toothfish (Dissostichus mawsoni), a commercially important and harvested species. Much of the toothfish life history is poorly or completely unknown.

Finally, the continental shelf is the most productive marginal sea in the Antarctic, with mean productivity estimates ranging from 120 – 160 g C m-2 yr-1. Productivity is limited in spring by irradiance (both by the presence of ice and by deep vertical mixing) and in summer by substantially reduced iron concentrations. Vertical flux rates of organic material are reported as substantial, and mesoscale and sub-mesoscale contributions to these fluxes have been suggested as being important.
Higher trophic levels reach substantial standing stocks as well (Smith et al., 2014a). Despite this, the food web is poorly characterized with critical uncertainties existing in our knowledge, especially with regard to energy and carbon transfer between trophic levels, the temporal and spatial variations in important species, and the ecological connections among important species (Figure 3).

The Ross Sea Marine Protected Area (MPA) has 11 specific objectives (CCAMLR conservation easure CM91-05), but has the broad aim protect and conserve the populations of Antarctic toothfish. Much of the Ross Sea continental shelf has been closed to fishing for many years, but the MPA creates regions designated for research and others that are closed to fishing. The life history of toothfish is very poorly documented, and it is controversial whether fishing has had an impact on the extant food web of the continental shelf and slope. The establishment of the MPA provides an opportunity to couple SOOS observational needs and designs with those of the CCAMLR scientific community.

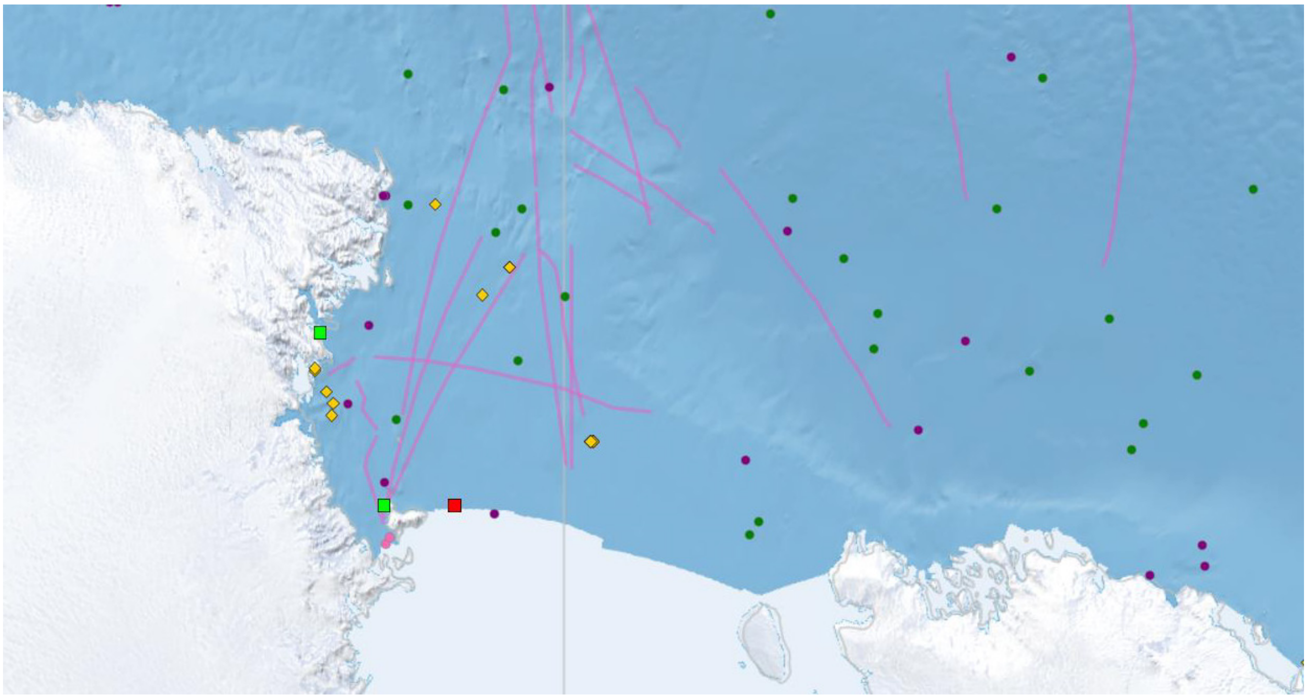

Figure 1: Locations of observations in the Ross Sea during 2017 in SOOSMap (www.soos.aq/ soosmap). Argo floats (green dots), Drifting buoys (purple dots), marine mammals (light pink), tide gauge (magenta), CAMLR Ecosystem (light green squares), radar (NECKLACE; red square), Moorings (yellow diamonds).

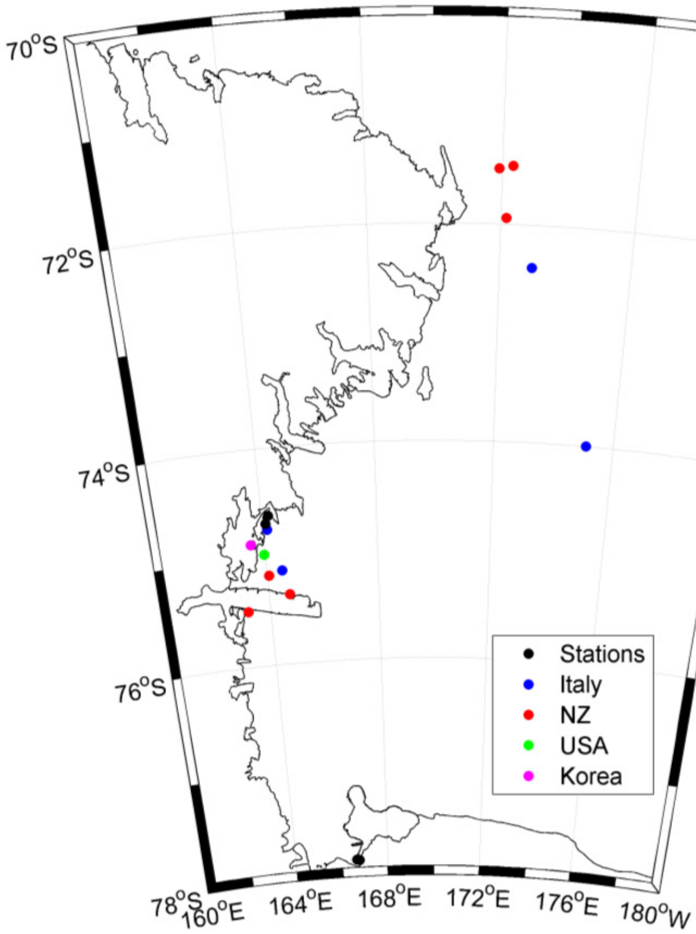


Figure 2: The locations of oceanographic moorings operating or planned for deployment in 2017-18.

Table 1: Locations of moorings currently deployed, or expected to be deployed in the Ross Sea.

| Mooring Name | Country | Latitude | Longitude | Status |
|---|---|---|---|---|
| L | Italy | 74°44.98’ S | 164°09.595’E | Deployed |
| G | Italy | 72°23.51’S | 172°59.135’ E | Deployed |
| B | Italy | 73°59.972’S | 175°06.031’ E | Deployed |
| D | Italy | 75°08.1442’S | 164°33.0659’E | Deployed |
| P1 | New Zealand | 71°29.304’S | 171°54.768’E | Scheduled Feb 2018 |
| P2 | Nea Zealand | 71°27.582’S | 172°18.276’E | Scheduled Feb 2018 |
| P3 | New Zealad | 71°56.61’S | 172°9.888’E | Scheduled Feb 2019 |
| HWD-2 | New Zealand | 80°39.858’S | 174°25.356’E | Deployed (not shown in Fig 1) |
| DITN | New Zealand/ Korea | 75° 21.612’S | 164°44.971’E | Deployed |
| DITS | New Zealand/ Korea | 75°29.305’S | 163°10.461’E | Deployed |
| DITD | New Zealand/ Korea | 75°16.542’S | 164°4.038’E | Deployed |
| LDEO | United State/ Korea | 74°58.47’S | 163°57.672’E | Deployed |
| Kamigod-II | Korea | 74°52.698’S | 163°31.5’E | Deployed |

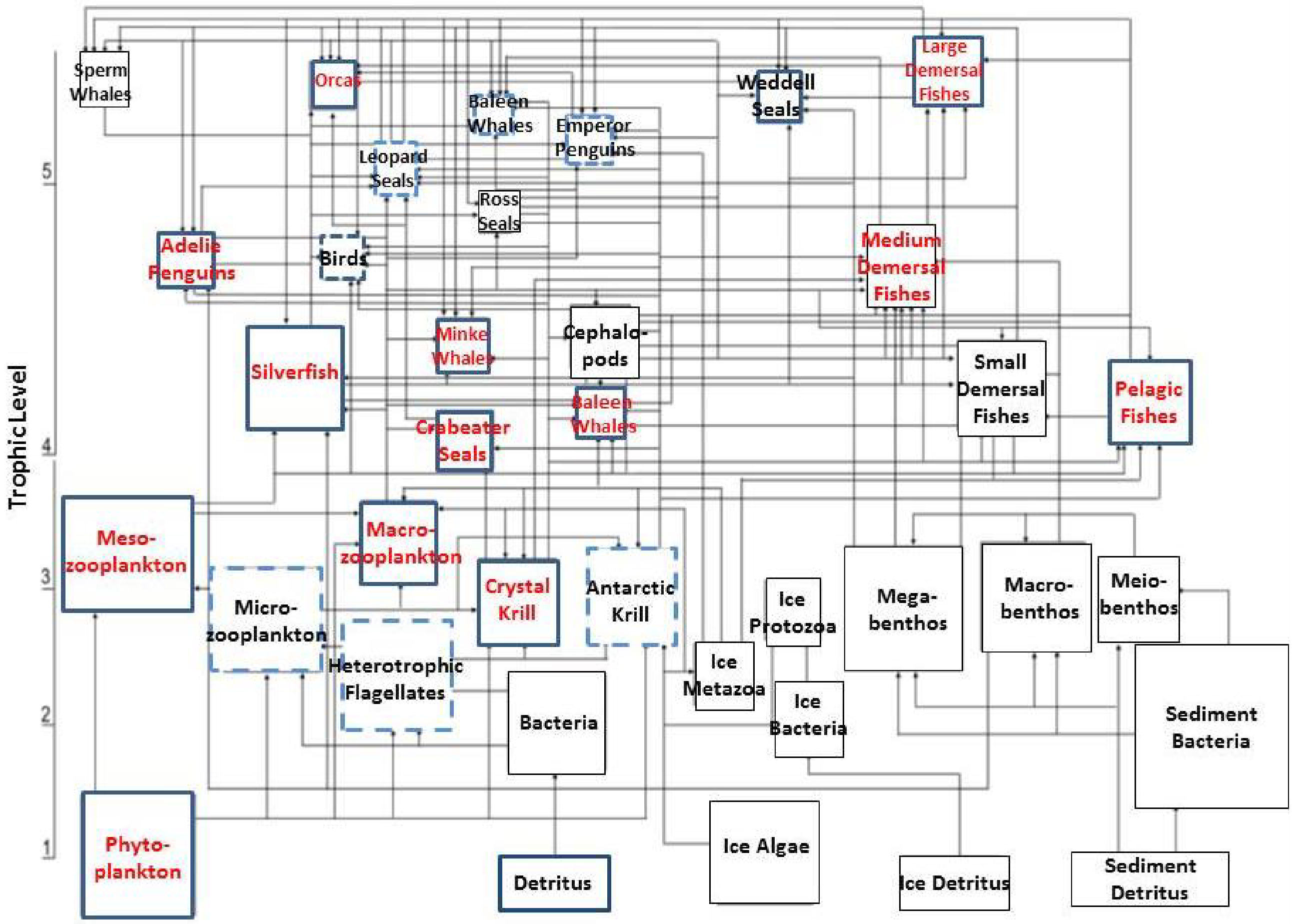


Figure 3. Hypothesized food web in the Ross Sea. Components in red are those that appear to have a major influence on the food web and the regional biogeochemistry. Adapted from Pinkerton et al. (2010).

## Field program 2018 and beyond:

*New Zealand*

In 2017, New Zealand announced new funding for Antarctic research that contains specific reference to supporting sustained observations. The expected call for proposals will not be before mid-2018 with the first field work anticipated in the 2019-20 summer season. This research funding is expected to support New Zealand researchers to develop proposals for observations in the Ross Sea, which will contribute to both to SOOS and the objectives of the Ross Sea MPA.

Current New Zealand research is supporting observations in sea ice, oceanography, and marine biology and fisheries. Fisheries time series are collected from the annual Ross Sea toothfish shelf survey, and are provided to CCAMLR to assist with the management of Antarctic toothfish. This survey monitors trends in the abundance of different year classes of fish.

Ongoing marine biological observations focus on the benthic infauna, epifauna, and habitat at Cape Evans in McMurdo Sound. They have been surveyed 8 times between 2001 and 2016. The primary science focus has been on understanding how benthic ecosystems will be affected by environmental change.

A sea-ice temperature probe is deployed most winters in McMurdo Sound to measure sea-ice growth rates and thickness. In complementary work, semi-regular electromagnetic "bird" measurements are flown over Southern McMurdo Sound. This work has primarily focused on the understanding and identifying the contribution of platelet ice driven by ice shelf water outflow from under the McMurdo ice shelf, but the area of interest is expected to expand in the future.

In collaboration with the Korean Polar Research Institute, two oceanographic moorings are currently maintained north and south of the Drygalski Ice Tongue and in 2018, had collected four years of data. Four new moorings are expected to be deployed in the 2017-18 summer. One will be through a hole in the Ross Ice Shelf, while the other three will be near Cape Adare and will be targeting the outflow of Antarctic Bottom Water. The mooring under the ice shelf is primarily exploratory in nature, but is expected to provide near real-time data for around 3 years. Semi-regular conductivity, temperature and depth (CTD) data are also collected in southern McMurdo Sound to support research into ice-ocean interaction processes and boundary layer flows under a range of ice regimes.

*United States*

The United States funds Antarctic research by peer review, and as such is less structured than international programs that are generated by organizations with specific, targeted research. Despite this, the US National Science Foundation has funded projects that make significant contribution to SOOS. One project is called CICLOPS (Cobalamin and Iron Co-limitation of Phytoplankton Species; G.R. DiTullio, PI). This project will be a Lagrangian study of the development of nutrient limitation within a patch of water as it evolves in time. The project will take place initially in Terra Nova Bay and will investigate the relationship of iron to blooms of Phaeoystis antarctica, a colonial haptophyte that is dominant during spring in the Ross Sea. They hypothesize that Phaeocystis becomes limited by iron, but that diatoms replace it and in turn become co-limited by iron and vitamin B12. Hence it will test the hypothesis that iron and Vitamin B12 co-limit phytoplankton production and species composition (Bertrand et al. 2007). The study will also include investigations of the molecular composition of the heterotrophic bacteria present that are hypothesized to mobilize B12 during bloom evolution. The ship will travel from Terra Nova Bay to Hobart, and thus monitor the open waters of the Ross Gyre north of the continental shelf.

A second program that is being led by the US is SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling). The project deploys a large suite of biogeochemical Argo floats in the Southern Ocean, collecting data from rofiling floats that sample from the surface to 1,000 m. Many of the floats have biological sensors as well, so the full suite of sensors on floats includes pressure, temperature, salinity, oxygen, fluorescence, nitrate, and pH. The latter two are novel inclusions on Argo floats and allow estimates of new production and carbon chemistry over large areas of the Southern Ocean. A few floats are capable of being deployed under the ice, but in large part most are in the ice-free waters of the ACC. Data are available in real time and with no restrictions. Substantial efforts have been in place with regard to sensor calibration and understanding potential sensor drift, but the program is a maor advance in providing new data for our understanding of the biogeochemistry of the Southern Ocean.

Additional programs have been proposed to NSF, but at this time the fate of those efforts remains uncertain. Expanding the community knowledge of the SOOS aims in the Ross Sea sector will facilitate the program's ability to achieve goals within US funded science efforts.

*China*

Chinese scientists are greatly interested in initiating comprehensive, interdisciplinary investigations in the Ross Sea to compliment other work they have conducted in Prydz Bay and the Antarctic Peninsula region. In addition, there are ambitious plans to build a research station on the coast of Victoria Land that will focus largely on biological and biogeochemical studies. China has at present a significant resource in its ice breaker R.V.I.B. Xue Long, and a second vessel will be completed in the coming year. During 2018, China will conduct an investigation into the neighbouring Amundsen Sea, and ambitious plans are being made to conduct a parallel investigation in the Ross Sea. Hydrographic stations are expected to be completed from the ice shelf (along 175°E, 170°W and 150°W) north to ca. 60°S, as well as a series along the ice shelf and near the coast of Victoria Land. More broadly China is anticipating deploying up to six moorings in a ring around Antarctica. Such investigations fit well with the overall SOOS objectives and will provide an excellent addition to the ongoing observations of other nations.

*Korea*

The Korean research program is collaborating with NZ and US scientists to support four ongoing moorings in the Terra Nova Bay region with the RV Araon. The collaboration with NZ supports moorings either side of the Drygalaki Ice Tongue and focusses on water mass transformation and modification along the base of the ice tongue and has had moorings deployed since December 2014. The collaboration with the US (Chris Zappa, LDEO) is focused on air-sea fluxes. Further moorings are deployed to support geological research. CTD data are collected in conjunction with mooring cruises providing an ongoing data set of variability in Terra Nova Bay. The RV Araon has also supported mooring deployments in other parts of the Ross Sea in collaboration with international researchers.

*Italy*

The Italian Programma Nazionale Di Ricerche in Antartide (PNRA) has supported an active observing program in the Southern Ocean and Ross Sea. Using the research vessel Italica, repeat XBT measurements have been recorded between New Zealand and Antarctica since 1994, and oceanographic moorings have been deployed since 1995 (Figure 1; Table 1). These are the two longest continuous observational ocean observations in the Ross Sea region. More than 1000 CTD profiles have been collected in the Ross Sea since 1994 on a regular basis during oceanographic basin wide cruises and during the moorings maintenance.

Recently Argo floats have been deployed in the Southern Ocean, and there are approximately 30 floats currently active in the Southern Ocean, most of which were deployed in the Ross Sea Sector. The replacement of Italica is anticipated to impact on the deployment of XBT's and Argo floats in the near future, but a replacement research vessel is expected soon and it is expected that PNRA will continue Argo, XBT, and mooring measurements once the replacement vessel is available.

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## Scientific drivers for an observing system in the Ross Sea:

Three overarching questions were developed and discussed in the workshop that require an observing system in the Ross Sea. The questions are:

1. How and when will change in the Ross Sea impact on the global ocean, and what will this impact be?
2. What will the impact of the changing Southern Ocean be on the Ross Sea and when and how will this occur?
3. How and when will change in the Ross Sea impact its biology and ecology, and what will those impacts be?

These questions capture these key ideas: how the Ross Sea is affected by change elsewhere and vice versa, and how change may present itself in the Ross Sea. They also reflect a need to understand rates of change, and the significance of change, both within the Ross Sea and outside the Ross Sea. These questions set a broad scope and ambition for an observing system in the Ross Sea, and it was recognised there where different levels of existing knowledge underpinning each question, with some disciplines still working on the discovery and identification of linkages and potential processes, and others at more advances stages with a focus on greater detail. To balance these needs, discipline-based hypotheses were developed to motivate funding applications for observing system components.

The questions were developed after three multidisciplinary subgroups identified numerous regionalscale science questions that motivate the need for an observing system within the individual disciplines. These questions were:

- How does the coverage (thickness, extent, concentration) of sea ice change?
- How does changing sea ice affect the Southern Ocean heat and fresh water budgets and what are the implications on circulation?
- What impact does freshening/weakening of AABW formation have on natural/ anthropogenic $CO_2$ uptake and storage?
- What are the sources of nutrients to the Ross Sea and how will/are these changing?
- What will happen to Ross Sea primary production in the future?
- What are the anticipated biological changes to the structure and functioning of the lower trophic levels?
- How will the mesopelagic biota (krill, silverfish) respond to changes in the physical system and in primary production?

- How will the efficiency of the biological pump change in response to the above?
- How does changing ocean chemistry (i.e., ocean acidification) impact the pelagic and benthic marine systems?

To address these questions, a number of topics were explored in detail, and specific hypotheses were formulated to address the need for monitoring efforts. Selected topics, their importance and the means for assessing the hypotheses are as follows:

*Shelf-break and shelf front boundary*

The dynamics on the Antarctic continental slope and the Antarctic Slope Front (ASF) are key for understanding interactions between waters on the continental shelf and in the Ross Gyre. Exchange across the ASF is hypothesised to effectively control warm water inflow onto the shelf, dense bottom water export, and the associated exchanges of heat, salt, oxygen and nutrients. Wind is thought to play the dominant role in driving the ASF around most of Antarctica, but this is not supported in regional ocean models. Alternative mechanisms in idealised models suggest that the ASF is controlled by the interaction of independent density driven process in the Ross Gyre and Ross Sea continental shelf. Processes at the shelf-break boundary are typically poorly resolved in models, as key processes occur at scales less than the resolution of most models. Hence, increased observations at suitable scales will support understanding the ASF, and at the larger scales confirm its role in controlling exchanges across the shelf break. Observations required to constrain climatescale models include pH, nitrate, and iron concentrations. Dense, off-shelf flow and the density structure within the Ross Gyre will require sustained Argo measurements, while the Slope front structure itself will require sustained glider observations.

*Fish*

Mesopelagic fish, such as silverfish (Pleuragramma antarcticum) and Electrona spp., have a biomass equivalent to or greater than that of krill in the Southern Ocean and have circumpolar distribution.
These species represent a key role in mediating the energy transfer between trophic levels, particularly when and where the biomass of krill is low. Mesopelagic fish species are major prey items of toothfish, pelagic birds, penguins, seals and whales, and are considered to be major factors in controlling food web yields and ecosystem stability throughout the Antarctic.

Potential changes in the physical environment, human impacts on predators, variations in fish distributions, and food web structure affect the ecological role of mesopelagic biota in the food web and their contribution to the biogeochemistry and carbon flux. A coordinated program monitoring the abundance and biomass over broad areas of the Ross Sea via acoustics and net sampling is needed, as well as continuous measurements at one location using moored acoustic sampling. Investigations intended to understand the spatio-temporal variations of food for mesopelagics would also be of great value. Such a program can be conducted in conjunction with CCAMLR and the Ross Sea MPA.

*Carbon*

Phytoplankton primary productivity supports the entire food web in the Ross Sea and has critical impacts on biogeochemical cycles. Primary production is directly impacted by sea ice and other physical drivers (winds, air-sea interactions), and these properties will be impacted by expected changes in the greater Southern Ocean. Changes in primary productivity will subsequently affect the net uptake of $CO_2$ will be altered, along with the composition of assemblages at different trophic levels and the flux of organic material to depth. Offshore transport will also be modified.

Increases in iron supply (dominated by changes in vertical resupply from water-column freshening, higher winds and glacial melt inputs), altered irradiance (dominated by changes in sea ice cover) and increased stratification (mixed layer depth) will likely increase net primary production and shift assemblage composition towards *Phaeocystis antarctica*. There are a number of potential implications of such changes – impacting the export of organic matter to depth and the biological pump; altering ecosystem structure, function and services; and modifying the timing and severity of ocean acidification. Critical gaps in our knowledge make credible predictions of future ecological changes in the Ross Sea difficult.

Continued process-based studies of phytoplankton abundance, distribution and growth are needed, along with a range of observations over a number of temporal scales: mesoscale, seasonal, interannual, and longer term. In addition, a coordinated effort to monitor one particular location (e.g., a transect off the coast of Victoria Land) to provide a time series of biological processes would be extremely beneficial. Such an effort could include moorings with sediment traps, profiling instrument packages, and autonomous vehicles to continually assess the space-time continuum. Satellite studies of pigments need to be continued and further evaluated and verified for the Ross Sea.

*Top Predators*

Top predators can be used as sentinels of ecosystem structure and dynamics because they integrate information across all trophic levels. Their distribution and abundance are determined by biological processes that result from the aggregation of prey, which in turn makes these zones areas of high ecological significance.

‘Hotspots’ of top predators occur in the Ross Sea and are characterised by bottom-up processes that determine the environment, as well as ecological dynamics of lower trophic levels in those areas. Predator distribution is a function of the interplay between the environmental features and the ecological interactions, and by understanding these structuring linkages the responses to environmental perturbations can be predicted.

A simultaneous assessment of the abundance and distribution of all top predators is required and can be derived from satellite, acoustic, and direct (airplanes, drones) observations. Multi-national process studies are needed to understand rates of consumption and turnover of key species in conjunction with an assessment of the specific environmental characteristics of the habitat.

In addition to these selected topics, additional areas of research needs were delineated:

- The observed variability and trend in sea ice is driven by natural tropical variability that is modulating and partially masking a forced response. The trend of expanding sea ice in the Ross Sea is likely to continue, perhaps for decades, before it reverses and becomes negative as the Ross Sea warms. Investigations are needed to assess the interactions among atmospheric processes on various scales, ice dynamics, and future changes in ice distributions.
- Seasonal advance and retreat of sea ice is driven by air-ice-ocean interactions at the ice edge, where outside of polynyas, these interactions are most vigorous. Yet ice edge processes are poorly observed and their role in ice edge variability is poorly understood. These processes drive a significant component of ice extent and ice- season duration variability
- The variability and timing of sea-ice production and melt in polynyas and at the ice edge significantly impacts Ross Sea ecosystem phenology, including both phytoplankton biomass, primary production, and middle and upper trophic levels. A clear understanding of the spatial relationships of all components of the food web is required to adequately predict the impact of future climatic changes.
- Changes in circulation and water mass properties exported from under the Ross Ice Shelf are driving observed changes in Antarctic Bottom Water. Knowledge relating ice shelf changes to overall physical conditions is essential to placing the Ross Sea in a global context.
- How will altered circulation and food delivery change benthic community composition and productivity? Given that changes in food quality and supply will occur in the near future, it can also be reasonably hypothesised that larval dispersal, survival and settlement patterns, post-settlement community composition, abundance, and diversity, post-settlement community reproductive potential, genetic characteristics of benthic community, and connectivity along and across coastal environments will be altered. Methods exist to adequately assess all of these relationships, but a coordinated program that includes all of the disparate benthic communities of the Ross Sea is required to adequately assess changes impact by climatic change.

## Potential components of an observing system for the Ross Sea:

The Ross Sea has several biologically and physically important sub-systems where observations should be focused year-round. These are:

- Large polynyas, which are important to sea-ice production and water mass transformations;
- Terra Nova Bay as a nursery for silverfish and a location of ecological richness;
- Boundaries of the Ross Sea including:
  - Ocean surface, including in the marginal ice
  - Land/cryosphere interface with the ocean,
  - Ice shelf front
  - Shelf Break
- Eastern part of the continental shelf; and
- The Ross Gyre

Full design of the physical and biogeochemistry components of an observing system in the Ross Sea would be best done with an Observing System Simulation Experiment (OSSE). While ideally this would be done in conjunction with a model intercomparsion experiment, significant progress could be made using a single data assimilating model that includes adequate representation of key processes including tides, mesoscale processes and mixed layer depth. Design of the biological components of an observing system requires a different approach to ensure it incorporates an adequate understanding of life history, foraging and other geographic constraints on the system. An example of an approach that could support observing system design is the use of Empirical Orthogonal Function analysis of key habitat predictors for a range of species.

While the need for an OSSE and similar analysis for biological systems was identified, significant progress was made in identifying key components of an ocean observing system. These include:

- Remote sensing, including being able to observe from non-satellite based systems that are not restricted by clouds;
- Weather data, including weather station, upper atmosphere and surface observations;
- Float technology, including Argo, Bio-Argo, Deep-Argo and surface drifters;
- Ship supported observations, including marine mammal and bird counts and Continuous Plankton Recorder (CPR) deployments;
- Animal sensors to observe both the environment and animal response to the environment;
- Integrated mooring systems to maximize data integration, potentially including upward looking sounders to measure ice draft;
- Gliders able to operate over both extended areas and extended periods, with newly developed sensors for biogeochemical variables;
- Autonomous Underwater Vehicles (AUV) and Remote Operated Vehicles (ROV) to facilitate access to difficult environments

(e.g., deep benthic and under ice shelf environments);

- Phase-sensitive radars for measuring ice shelf melt rates;
- Time series stations co-located with moorings in key environments to augment monitoring of ecosystem processes; and
- Terrestrial and distributed data transfer networks to provide increased band-width from observational systems to data repositories.

To support this observational network, an international consortium for shipboard operations should

be considered, particularly to support mooring turnarounds, time series stations, and extended

glider deployments. This should be integrated with Antarctic logistics so that multimode

deployments and retrievals (e.g., to or from sea ice or coastal stations) can be integrated.

## Future Plans:

Continued development of an observing system in the Ross Sea is contingent on funding. Science seeking discovery was identified as the most common funding mechanism within the countries represented at workshop. The long-established Bermuda and Hawaii ocean time series were cited as analogies where discovery-driven science supported and contributed to the establishment of the time series. Projects were able to develop inherent value for future science based on the context the ongoing observations provided. To motivate proposals that will develop and establish an observing system, hypotheses were developed in different disciplines that are scientifically independent, but at the same time seek to answer the larger questions that drive the need for an observing system in the Ross Sea.

These projects could achieve significantly larger international scale if supported by more than one country. Typically, this is done by through multiple proposals in different countries, albeit creating additional risk if one or more components are not supported. An alternative proposed model was to encourage collaboration between funding agencies, an example being joint US-UK support for research in the Amundsen-Bellinghausen Sea. Development of such a model is difficult and unlikely to include all countries; regardless, the workshop concluded that it is critical to facilitate more coordinated proposal development.

Existing national observing efforts, for example the Italian mooring program, are expected to continue, and can serve as “backbones” for observing efforts. Identifying multiple “backbones” for an observing system could provide a potential framework for national programs to integrate into an observing system.

Workshop attendees expressed interest in continuing as members of the Ross Sea

Working Group, with Walker Smith and Mike Williams continuing as co-chairs. In terms of actions for the working group, the main objectives were:

- The preparation and dissemination of this report;
- Preparation of a summary document that could be submitted to newsletters with a broad audience, such as American Geophysical Union's EOS, to provide a more easily citable summary of the workshop outputs and notification of a large community of SOOS efforts;
- Continuing to engage with CCAMLR concerning the development of the Ross Sea Marine Protected Area Research and Monitoring Plan, especially with regard to specific research and observational efforts; and
- Organization of a subsequent meeting if and when there is a clear need. Giorgio Budillon offered for Italy to host the next meeting.
- Identify "backbone" observations in the Ross Sea region.

## Issues and recommendations:

The following recommendations were agreed upon at the conclusion of the workshop:

1. Given the present rates of change within the Southern Ocean and in particular the Ross Sea, and the potential for significant global impacts, an international, multidisciplinary program to monitor the expected changes is necessary to provide assessments of change rates and provide data to generate credible projections for future states;
2. Integrated, international cooperation is essential to the formation of various aspects of monitoring climate change and should be initiated and formulated at the highest levels of governments;
3. Close coordination with CCAMLR and the Ross Sea MPA should be continued and expanded;
4. Investigations should include all temporal scales (from days, weeks, months, seasons, years, and decades) and a large spatial scale to include the ice shelf (and waters beneath it), the continental shelf, and the deeper aters and islands of the northern Ross Sea Sector; and
5. Understanding the linkages among physical processes, biogeochemical cycles, and biological processes should be essential components of all national and international efforts in the Ross Sea.

## Appendix 1: Sponsors

Agencies and offices which contributed financial support for the SOOS Shanghai workshop.

| **Supporting Agency** | **Location** |
|---|---|
| Institute of Oceanography, Shanghai Jiao Tong University | Shanghai, PRC |
| Ocean Carbon and Biogeochemistry Office | Woods Hole, MA, USA |
| Southern Ocean Observing System International Project Office | Hobart, Australia |
| Second Institute of Oceanography | Hangzhou, PRC |
| National Laboratory for Marine Sciences and Technology | Qingdao, PRC |

## Appendix 2: References


Arrigo, K.R., G. van Dijken, and M. Long. 2008. Coastal Southern Ocean: a strong anthropogenic $CO_2$ sink. Geophys. Res. Lett. 35: 1–6, doi.org/10.1029/2008GL035624.

Bertrand, E.M., M.A. Saito, J.M. Rose, C.R. Riesselman, M.C. Lohan, A.E. Noble, P.A. Lee and G.R. DiTullio. 2007. Vitamin B12 and iron colimitation of phytoplankton growth in the Ross Sea. Limnol. Oceanogr. 52: 1079-1093.

Bracegirdle, T.J., and D. B. Stephenson. 2012. Higher precision estimates of regional polar warming by ensemble regression of climate model projections. Clim. Dyn., 39: 2805–2821, doi:10.1007/S00382-012-1339-3.

Pinkerton, M.H., J.M. Bradford-Grieve, and S.M. Hanchet. 2010. A balanced model of the food web of the Ross Sea, Antarctica. CCAMLR Sci. 17: 1–31.

Smith, W.O. Jr., D.G. Ainley, K.R. Arrigo, and M.S. Dinniman. 2014a. The oceanography and ecology of the Ross Sea. Annu. Rev. Mar. Sci. 6: 469-487.

Smith et al. 2014b. The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. Geophys. Res. Lett., 41, 1624–1631, doi:10.1002/2014GL059311.

Stammerjohn, S., R. Massom, D. Rind and D Martinson. 2012. Regions of rapid sea ice change: an interhemispheric seasonal comparison. Geophys. Res. Lett., 39, L06501, doi:10.1029/2012GL050874.

# Appendix 3: Workshop Schedule and Program

**10 September 2017 6 pm–10 pm: *Icebreaker & registration***

Location: Tavern Bar & Grill at Radisson Blu Hotel (Xingguo Hotel)

**11 September 2017: Day 1**

Location: 2nd floor Ballroom, Radisson Blu Hotel (Xingguo Hotel)

| | **Scope** | **Proposed Presenter** |
|---|---|---|
| ***Welcome and Overview (Chaired by Zhou)*** | | |
| 8:30 | Introduction to local contacts & logistics | Meng Zhou, SJTU |
| 8:35 | Opening remarks | Dr. Jun Wu, Vice Director of CAAA |
| 8:45 | China's potential contribution to SOOS | Dr. Dake Chen, China SOOS representative |
| 9:00 | Participant self-introductions | Workshop attendees |
| 9:15 | SOOS Regional Working Groups | Mike Williams |
| 9:30 | Ross Sea WG and objectives | Walker Smith/Mike Williams |
| ***Physical Oceanography in the Ross Sea (Chaired by Smith)*** | | |
| 9:45 | Overview of Ross Sea continental shelf circulation and unknowns | Giorgio Budillon |
| 10:15 | Ross ice shelf: circulation and impacts | Mike Williams |
| **10:30** | *Coffee/Tea* | |
| 11:00 | Overview of sea ice distributions and its patterns in the Ross Sea sector; link to climate change | Ted Maksym |
| 11:30 | Models of the Ross Sea and its linkages to the Southern Ocean | Eileen Hofmann |
| **12:00** | *Lunch at Cafe Li on the 1st floor. Please pick up the lunch coupon from the workshop manager.* | |
| 1:30 | SOCCOM floats in the Ross Sea sector: initial results | Joellen Russell |

| | | |
|---|---|---|
| 2:30 | Phytoplankton and biogeochemistry in the Ross Sea sector - Unknowns | Walker Smith |
| 3:00 | Vertical fluxes in the Ross Sea sector | Leonardo Langone |
| **3:30** | *Coffee/Tea* | |
| 4:00 | Krill in the Ross Sea - Unknowns and spatial distributions | Kendra Daly |
| 4:15 | Potential contributions of fisheries acoustics to SOOS in the Ross Sea region | Xianyong Zhao |
| 4:30 | State of the Art in satellite sensing of sea ice | Wolfgang Rack |
| 5:00 | Model and observation activities of First Institute of Oceanography in Polar Area | Fangli Qiao |
| **6:00** | *Bus depart for the conference banquet* | Workshop banquet at Yu Jing Tian by the Bund |

**12 September 2017: Day 2**

Location: 2nd floor Ballroom, Radisson Blu Hotel (Xingguo Hotel)

| | | |
|---|---|---|
| ***Biogeochemical Oceanography in the Ross Sea (Chaired by Williams)*** | | |
| 8:30 | Oceanographic moorings as platforms for settlement dynamics of Antarctic invertebrates: a new potentiality for long-term monitoring programs | Sefano Schiaparelli |
| 8:50 | Potential role of off-shelf transport by fish | |
| 9:10 | Seals as oceanographic sensors | Kim Goetz |
| ***International Observing Programs in the Ross Sea (Chaired by Williams)*** | | |
| 9:30 | CCAMLR MPA | Video presentation: Alistair Dunn |
| 10:00 | SOOS OASIIS (Observing and Understanding the Ocean below Antarctic Sea Ice and Ice Shelves) Working Group | Jiuxin Shi |
| 10:15 | ANTOS (Antarctic Near-shore and Terrestrial Observing System) | Vonda Cummings |

| | | |
|---|---|---|
| **10:30** | *Coffee/Tea* | |
| ***Chinese Research and Activities in the Antarctic and Ross Sea (Chaired by Smith)*** | | |
| 11:00 | Observation and research activity at Center for Southern Hemisphere Ocean Research | Cai Wenju |
| 11:15 | Air-Sea fluxes of carbon, sulfur, and iron in the continental shelves in the Antarctic | Liqi Chen |
| 11:30 | Rotating horizontal convection and the potential vorticity constraint: implications for Ross Sea | Yu Zhang |
| 11:45 | Development and application of fully automatic underway systems for observation of climate-sensitive chemical species | Liyang Zhan |
| **12:00** | *Lunch at Li Palace (丽宫) on the 4th floor. Please pick up the lunch coupon from the workshop manager.* | |
| ***Observing Programs in the Ross Sea - status and plans (Chaired by Zhou)*** | | |
| 1:30 | New Zealand activities in the Ross Sea | Mike Williams |
| 1:45 | United States activities in the Ross Sea | Joellen Russel/Walker Smith |
| 2:00 | Korean activities in the Ross Sea | Won Sang Lee |
| 2:15 | Italian activities in the Ross Sea | Giorgio Budillon |
| 2:30 | Chinese activities in the Ross Sea | Tijun Zhang |
| ***Subgroups discussions on science drivers (Chaired by Williams)*** | | |
| 2:45 | Key science drivers and prioritization of research questions | Mike Williams (break into 3 discussion groups) |
| **3:45** | *Coffee/Tea* | |
| 4:00 | Report back from subgroups | Group leaders |
| 5:30 | End of the day | Dinner on your own; river cruise (option) |

**13 September 2017: Day 3**

Location: 2nd floor Ballroom, Radisson Blu Hotel (Xingguo Hotel)

| | | |
|---|---|---|
| ***Plenary discussions on science drivers (Chaired by Smith)*** | | |
| 8:30 | Recap of days 1 and 2; Discussion: 1) Key state variables & processess in the Ross Sea; 2) Spatial & temporal scales f key processes; 3) Key monitoring facilities, equipment & technology needs | Williams/Smith/Budillon/Qhou |
| **10:30** | *Coffee/Tea* | |
| 11:00 | Designing a strategy for system implementation | |
| **12:00** | *Lunch at Cafe Li on the 1st floor. Please pick up the lunch coupon from the workshop manager.* | |
| ***Plenary discussions on future implementation and activities (Chaired by Williams)*** | | |
| 1:30 | Designing a strategy for system implementation: international collaboration and organisation | |
| 3:00 | Outline of the workshop report | Mike Williams/Walker Smith |
| **3:30** | *Coffee/Tea* | |
| 4:00 | Establishing the Working Group | Mike Williams |
| 5:00 | Workshop close & logistics | Meng Zhou |

## Appendix 4: Presentation summaries

Summaries of key background scientific presentations at the workshop as provided by the speakers in the order presented at the workshop:

*Overview of Ross Sea continental shelf circulation and unknowns, Giorgio Budillon*
It is well known that the Ross Sea circulation and hydrology is dominated by the presence of polynyas, strong air-ice-sea interactions and by the inflow of the relatively warm, salty and nutrient rich Circumpolar Deep Water (CDW). Moreover, the presence of three submarine ridges that run from southwest to northeast constitute a strong constrains for the deep circulation. The Ross Sea is covered with sea ice for much of the year; sea ice concentrations are strongly influenced by winds. The presence of the Ross Ice Shelf constitutes not only the physical southern border for the Ross Sea but it is also the boundary of the oceanographic understanding. The identification of trends in thermohaline properties and in some biogeochemical parameters, clearly indicates that the whole Ross Sea is still far from the steady state, it is very sensitive to the climate changes, and it needs more investigations to better understand cause-effect relationships.

While we now have a reasonable conceptual understanding of Antarctic Bottom Water (AABW) production in the Ross Sea, further progresses are hampered by a paucity of data due, in part, to the wide range of scales of this phenomena that varies from tidal to interdecadal in time and from less the Rossby radius (less than 5 km) to the regional scale in space. Antarctic Surface Water input along the slope and coastal currents with increasing amounts of meltwater and precipitation, either exported in the Amundsen Sea or gained during transit, are likely the largest contributors for such freshening.

The Ross Sea continental shelf is well studied compared to other regions of Antarctica, however observations remain biased to the western side and in the austral summer period.

The eastern side of the shelf is still a challenging environment to undertake observations due to the heavy ice cover even in summer.

Few studies have been made recently toward characterization of high frequency and mesoscale ariability in the Ross Sea. Study of high-frequency and small-scale variations in the ocean is facilitated by the use of autonomous observing platforms such as gliders, whose use is becoming more common in regional studies in polar areas.

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. This procedure will be invaluable, using data acquired from moorings, hydrographic surveys, glider surveys, and satellite information, to build a full three-dimensional model to investigate the present and future changes.

*Understanding the ocean under the Ross Ice Shelf, Mike Williams (NIWA)*

The Ross Sea extends into the cavity under the Ross Ice Shelf, an area similar in size to Spain. Observations of this cavity are difficult to make and sustain, because of the thickness of the ice shelf. In 2017 a fourth hole will be made through the Ross Ice Shelf, this will be the second to attempt sustained moored observations. The first was near the front of the Ross Ice Shelf near Ross Island, where 5 years of current meter and temperature, 4 years of ice shelf ablation and ~18 months of salinity data were collected. This data highlights both the variability at interannual, seasonal and tidal time scales. It also shows the links between surface water in the Ross Sea Polynya and the cavity. The first hole at J9 in the 1970s showed a dominant two-layer structure within the ice cavity with comparatively warm High Salinity Shelf Water flowing at the bottom and colder fresher ice shelf water on the top. The only other observations under the Ross Ice shelf have been made near the grounding line of the Whillans Ice Shelf in a comparing thin water column, and are yet to be published. Several holes have also been made through the McMurdo Ice Shelf, and have shown the connection between McMurdo Sound and the Ross Ice Shelf cavity. Phase sensitive radar measurements have also been used to infer circulation by looking at basal ablation rates. However, these seem of most use for validating ocean models. Models, which while sensitive to the often poorly know sea floor and ice base topography, remain the most common tool for understanding circulation under ice shelves.

*Sea ice properties, variability and trends and new observations, Ted Maksym (WHOI)*

In situ observations of sea ice in the Ross Sea have been made infrequently, with the bulk made in the 1990s. The ice cover properties are shaped by the relatively sheltered embayment and continual northward drift of sea ice away from the coast, where ice production is dominated by the two major polynyas – the Ross Ice Shelf Polynya, and the Terra Nova Bay Polynya - which contribute as much as 40% of the ice production in the Ross Sea. These conditions lead to a non-monotonic gradient in ice thickness, with thinner ice at the ice edge and at the coast, and the thickest ice in the central Ross Sea, with thicker sea ice also imported from the Amundsen Sea. Significant increases in ice extent and ice season duration have been observed over the past four decades that are most conspicuously for this region not captured in climate models, although proxy data suggest ice extent may have been greater in the mid-20th century. These changes have been accompanied by significant trends in northward ice drift and ice production in the polynyas, with a likely accompanying increase in ice thickness. A definitive explanation for observed trends has been elusive, but both changes in intensifying westerly winds and accompanying increased northward sea ice export, and influence of tropical variability are prime factors, with ocean feedbacks likely playing a significant role. However, interannual variability is large relative to trends, with varying patterns of atmospheric variability driving individual seasonal anomalies. Motivated by these trends, a recent effort to better understand winter sea ice processes and air-ice-ocean interactions within the polynyas and the ice pack was undertaken in April-June 2017 (PIPERS). This year was characterized by an anomalously low sea ice extent, which led to a relatively thin, mobile and dynamic pack, with very high ice production observed in the polynyas. The experiment used a multiplatform approach, with a variety of measurements taken from a variety of autonomous vehicles and drifting buoys and high-resolution satellite imagery, providing a potential starting point for a sea ice component to an observing system for the Ross Sea.

*Models of the Ross Sea and its linkages to the Southern Ocean, Eileen Hofmann (ODU)*
The Ross Sea is undergoing rapid changes in ocean temperature and seasonal ice cover which have the potential for producing significant changes at all trophic levels. Models that simulate environmental conditions and are coupled to biogeochemical and food web models provide a framework that can be used to understand and project the effects of these changes. High-resolution (4-5 km horizontal resolution) circulation models have been implemented for the Ross Sea and the Southern Ocean. The circulation models include dynamic sea ice and atmospheric coupling; the Ross Sea circulation model includes ice shelf processes. These models provide insights into transport pathways (e.g. CDW inputs), export to/from the Ross Sea, general understanding of circulation dynamics, and the ability to project future conditions. Lagrangian simulations using the circulation models allow investigation of the transport and fate of early life history stages of important species, such as Antarctic krill and toothfish. These results show regional hot spots in the Ross Sea for key species and connection to the larger Southern Ocean system. Biogeochemical models implemented for the Ross Sea provide understanding of controls on primary production as well as the role of iron in limiting this production. Simulations with these models show clearly the importance of environmental conditions (e.g. mixed layer depth) and the relative importance of different iron sources (e.g. sea ice, benthic) in controlling the timing and magnitude of phytoplankton blooms. The development of food web models for the Ross Sea remains to be done, and an important aspect of developing these models is understanding the habitat characteristics that control the distributions of key species. Advancement and implementation of models for the Ross Sea will benefit from 1) retrospective studies that identify basic patterns and processes, 2) community-based development of a set of agreed scenarios, and 3) development of an overall strategy to ensure that observational and modelling programs are coordinated.

*The role of iron in the Ross Sea sector, Peter Sedwick (ODU)*
In the Ross Sea sector of the Southern Ocean, the supply of dissolved iron, an essential micronutrient, plays a major role in regulating primary production, hence biological carbon uptake and the larger Southern Ocean ecosystem. In the high-nutrient low-chlorophyll waters north of the continental shelf, phytoplankton are likely subject to chronic iron deficiency during the growing season. In the highly productive high-nutrient high-chlorophyll waters over the Ross Sea continental shelf, however, phytoplankton are thought to suffer seasonal iron limitation: Dissolved iron concentrations are elevated (~0.3 nM) in the euphotic zone in early spring, presumably as a result of vertical resupply from the benthos by winter convective mixing, but are rapidly drawn down to growth-limiting concentrations (~0.1 nM) by intense phytoplankton blooms as the Ross Sea polynya opens. Despite this, algal biomass continues to accumulate in austral summer, suggesting some input of dissolved iron to surface waters during the growing season. A recent study combining targeted field observations and a high-resolution physical model of the Ross Sea shelf indicates that winter vertical resupply and melting of sea ice are the main sources of dissolved iron to surface waters during the growing season, with an additional significant contribution from upwelling of Modified

Circumpolar Deep Water, and only minor inputs from glacial melt water. Other recent results suggest that vertical turbulent diffusion from subsurface waters and the recycling of biogenic particulate iron might constitute important sources of dissolved iron during the growing season. A number of questions remain to be answered regarding iron and its current and future impact on primary production over the Ross Sea continental shelf, including (1) the magnitude and spatial extent of the vertical resupply of benthic iron; (2) the extent and timing of seasonal sea ice melting and iron release; (3) the biological availability of the relatively large particulate iron pool in surface waters; and (4) the importance of subglacial melt water as a source of iron. Questions (1) and (2) are of particular relevance to the SOOS mission.

*Phytoplankton and biogeochemistry in the Ross Sea sector – Unknowns; Walker Smith (VIMS)*

The Ross Sea continental shelf has been studied intensively for decades, and much is known about ts physical oceanography, ice conditions, biogeochemistry and the biological temporal patterns (both seasonal and interannual). It has been a primary region where distributions and controls of iron have been assessed, but far less attention has been given to the deeper portions of the continental slope and waters to the north of the shelf break. Models of the circulation and the interaction with both offshore and under ice waters are available, making predictions of future change possible; however, uncertainties and unknowns remain and need to be addressed before a full understanding of the food web and its biogeochemistry, and potential future changes, can be determined. Temporal patterns of phytoplankton composition were discussed, emphasizing the spring appearance of the haptophyte Phaeocystis antarctica, followed by the appearance of diatoms. Spring growth is largely limited by irradiance, while summer growth appears to be iron limited. However, detailed analyses of these patterns showed some striking inconsistencies. For example, nitrate removal, chlorophyll increases, and net community production continued for at least 4 weeks after iron had been reduced to less than 0.06 nM. The potential of intercolonial iron cycling was discussed. Diatoms also increase markedly in summer, but chlorophyll increases are far less, suggesting a marked change in the carbon:chlorophyll ratio in response to iron limitation. Finally, inconsistencies in the mesoscale distribution of organic matter measured by gliders with sediment trap results suggests that vertical flux rates are far more variable in space and time than previously suggested. Investigations of these patterns on small space and times scales are urgently needed.

*Vertical fluxes in the Ross Sea sector, Leonardo Langone*

Particle fluxes in the Ross Sea based on data from time-series sediment traps (23 sites, >1000 samples) highlight some important features and unresolved issues related to export fluxes. Annual organic carbon fluxes to 200 meters average 4.4±3.3 g C m-2 yr-1, which are significantly less than export fluxes calculated using biogeochemical techniques. Sediment trap data show relatively low sedimentation rates during the periods of high primary production in surface waters, followed by enhanced sedimentation periods during late summer/autumn. This high degree of decoupling between production and sedimentation may represent low grazing rates and late-summer algal blooms stimulated by katabatic winds. Compared to the Ross Sea, biogenic fluxes in the Antarctic Peninsula are higher, but are more tightly coupled to surface productivity. The high interannual variability is linked to the factors driving sea ice cover and phytoplankton production, such as atmospheric forcing. The pattern of spatial variability of vertical fluxes shows South-North and coast-to-open ocean gradients that are likely related to polynya dynamics, which in turn play a role in regulating the biological production. Lateral advection of particles influences size and composition of particle fluxes collected by near-bottom traps. When diatoms are dominant, fluxes of fecal pellets are larger. A long–term trend of export fluxes is not apparent. Annual fluxes have been increasing during the ’90, but decreasing after 2000. It is unknown if this pattern is transient or how fluxes will change in the future.

*Krill in the Ross Sea - Unknowns and spatial distributions; Kendra Daly*

Two major krill species occur in the Ross Sea: Euphausia superba (Antarctic krill) and E. crystallorophias (crystal krill). They have been observed using multiple sampling devices in the past. The two species usually are spatially segregated, with E. superba largely restricted to the deeper waters near the shelf break. Concentrations range up to 12,000 ind m-2. Crystal krill occur over the entire continental shelf, with larger accumulations having been found on shallow banks and near the Ross Ice Shelf. Distributions are influenced by those of predators (penguins and seals), and often are associated with ice. Both species aggregate into swarms and layers, and may both feed on the under surface of ice as well as on phytodetritus in sediments. Given the critical importance in food webs, more detailed analysis of their distributions abundance, growth and survival strategies is warranted.

*Sea Ice: Essential climate variable from satellite; Wolfgang Rack*

The longest and best resolved satellite derived climate variables from satellite are the daily records of sea ice extent and concentration over a period of four decades. As global circulation models are unable to resolve at present the Southern Ocean trends in sea ice extent the question arises if critical sea ice variables are not adequately captured in the required detail. The main candidates are ice thickness, floe size related variables in the marginal ice zone (MIZ), and ice deformation. Observation of these variables requires application of new satellite technologies and on or near ice validation. This presentation summarizes selected main sources of satellite products for the sea ice community and showcases advances and needs in the measurement of sea ice freeboard and wave observations in the marginal ice zone. Validation activities using airborne and new UAV technology for ice thickness measurements in the Southwestern Ross Sea are illustrated.

*The role of upper trophic levels on Ross Sea biogeochemistry, Walker Smith (VIMS) and Kendra Daly (USF)*

Although much is known concerning the ecology, standing stocks, and distributions of Ross Sea higher trophic levels, next to nothing is known concerning their impacts on biogeochemical cycles in the region. Given the large standing stocks of Emperor and Adélie penguins, seals (crabeaters and Weddell), whales (baleen and toothed), pelagic birds, and fish (Antarctic toothfish), these animals conceivably can modify the distribution of elements in both time and space. Examples of biogeochemical impacts presented included surface water iron fertilization by baleen whales, and the enhanced $CO_2$ fluxes as a result of higher trophic level respiration. Standing stocks of higher trophic levels are among the greatest in the world and in the Antarctic, so if such effects were to be shown as being important, the Ross Sea should be a region where these impacts are evident and significant.

*Model and observation activities of First Institute of Oceanography in Polar Areas; Fangli Qiao*

The model development and observational activities in the Southern Ocean were introduced. As the simulated mixed layer depth in austral summer in the upper ocean is too shallow for nearly all ocean and climate models, the non-breaking surface wave-induced vertical mixing may help explain this discrepancy, which is confirmed by ocean and climate models.

*Oceanographic moorings as platforms for settlement dynamics of Antarctic invertebrates: a new potentiality for long-term monitoring programs; Stefano Schiaparelli*

Oceanographic moorings are used as in situ observatories in selected areas to measure and record water column features. However, they also represent artificial hard substrates that are colonized by larvae and function as 'stepping stones' in dispersal trajectories of invertebrates. Moorings have been augmented to include a cage experiment and the study of benthic settlement dynamics. These studies focused on the Antarctic scallop Adamussium colbecki, which was caged with 60 specimens, 58 of which have been retrieved alive. The shells of these specimens were studied for growth and their trace elements/isotopes used to evaluate the water column features, which were crosschecked with the instrumental data collected on the mooring. Moorings can easily be adapted to host caging experiments and panels for the settlement of invertebrates. The systematic use of these 'modified' moorings has several advantages: i) it is cost effective and takes advantage of already existing mooring networks; ii) could be extended to the study of microbes through a metabarcoding approach; iii) biological data are collected simultaneously with physical variables; iv) it will allow the tracking of dispersal routes of key species having a broad distributions and characterize the spectrum of species that is 'typically dispersed' by a given water mass, and; v) it will guarantee a long-term monitoring of settlement dynamics of key invertebrate species representing an early sentinel system to detect changes in the biological component.

*Potential role of off-shelf transport by fish; Meng Zhou (SJTU)*

Mesopelagic fish constitutes more than 95% of fish biomass in the global ocean. In Antarctica, it is well known that mesopelagic fish, such as silver fish, plays a critical role in the food web preying on krill while being predated as one of predominant preys by toothfish, penguins, seals and whales. Recent studies revealed that the biomass of mesopelagic fish is 10-30 times more than previous estimates of 2-6 g wet weight m-2. They also exhibit diel migration patterns not only vertically between the surface water and mesopelagic zone, but also horizontally between shelves and shelf breaks. Several recent studies on mesopelagic fish in the North Atlantic, North Pacific and South China Sea have revealed that the vertical migration of mesopelagic fish contributes significantly to vertical carbon flux into deep oceans and the horizontal migration of mesopelagic fish contributes significantly to cross-shelf break transport of biomass. The biological transport associated with mesopelagic fish and biological transformation mediated between krill and higher trophic level organisms in the Southern Ocean are of critical mechanisms for understanding ecosystem functioning, productivity and stability of the Marine Protected Areas in the Southern Ocean.

*Seals as oceanographic sensors Kim Goetz (NIWA; with Daniel Costa & Luis Huckstadt,,UCSC)*

Oceanographic sensors attached to seals are providing data in areas where traditional shipboard and Argo-float coverage is limited, absent, or logistically unfeasible. In addition, these tags offer a significant advantage over other oceanographic technologies by collecting data at the same spatial temporal resolution as animal behaviour. While several tags are able to collect temperature data, Conductivity Temperature Depth - Satellite Relay Data Loggers (CTD-SRDL, manufactured by Sea Mammal Research Unit at University of Saint Andrews) are the only tags to incorporate a miniaturized CTD unit. Since 2004, the deployment of CTD tags on animals has resulted in more than 500,000 vertical casts and compose over 70 % of the oceanographic data south of 60˚ S in the World's Ocean Database. Although sensor calibration or data post-processing is often necessary to improve data accuracy depending on the environment being measured and the behaviour of the animal, the offset of animal-borne CTD data is predictable and correctable. As a result, using seals as oceanographic platforms provides an accurate and often the only means to collect high-quality data in remote locations especially during the winter when heavy ice prevails. For example, over 18,000 CTD casts have been collected by 59 Weddell seals on the western Ross Sea shelf from 2010 to 2012, offering the only overwinter data on both oceanography and seal behaviour. These data were crucial in determining behaviour and habitat utilization of Weddell seals in addition to refining Ross Sea oceanographic models. While CTD tags continue to be improved, advancements in tagging technology are also enabling the collection of a new suite of data (flourometry, oxygen, acoustics, and video) and therefore providing additional opportunities to address oceanographic and ecological questions at the level of animal behaviour.

*Observation and Research Activity at Centre for Southern Hemisphere Ocean Research; Cai Wenju (Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia &Qingdao National Laboratory of Marine Science and Technology (QNLM) China)*

The Southern Ocean is a major sequestrator of heat and carbon, plays an important role in global overturning circulation, and strongly interacts with processes influencing variability and change of the Antarctic ice shelf and marine ice sheet. However, our understanding of the role of the Southern Ocean in regional and global climate remains limited. In 2016 CSIRO and QNLM entered into a collaborative agreement to co-invest in Southern Hemisphere Oceans research, focusing on Southern Ocean water masses, Southern Ocean processes, and sea level variability and change taking into account the contribution from Antarctic ice sheet. A particular focus is on Southern Ocean observations using various platforms including deep Argo and under-ice Argo.

*Air-Sea fluxes of Carbon, Sulfur, and Iron in the continental shelves in the Antarctic; Liqi Chen*

The Southern Ocean strongly influences climate patterns and the cycling of carbon and nutrients. Changes in the Southern Ocean therefore have global ramifications. The uptake of carbon by the Southern Ocean has slowed the rate of atmospheric climate change, but caused basin-wide ocean acidification, and Southern Ocean ecosystems are reacting to changes in the physical and chemical environment. Therefore, we have begun to address the consequences of Southern Ocean carbon uptake, ocean acidification and their impacts on climate-sensitive chemical species biogeochemical cycles. Surveys within the Southern Ocean have been conducted with underway observations and focused on the distributions of $pCO_2$, air-sea $CO_2$ fluxes and their controlling factors. The results show that: 1) a weakening of $CO_2$ sequestration in the Southern Ocean from 1999 to 2016; 2) an undersaturation of $N_2O$ south of the Subantarctic Front (SAF) due to a combination of SST variation and intrusion of $N_2O$-depleted ice meltwater during summer; 3) no significant correlation between MSA/nss-$SO_4$ and air temperature at high latitudes indicating latitudinal temperature variations were not a main factor responsible for the MSA/nss-$SO_4$ variation in the high latitudes; and 4) the estimated deposition fluxes of total dissolved Fe were from 0.01 to 0.56 mg m-2 yr-1 over the Southern Ocean; and 5)a strong anti-correlation between surface dimethyl sulfide and partial pressure of carbon dioxide in marginal ice zone of the Southern Ocean.

*Development and Application of Fully Automatic Underway Systems for Observation of Climate- Sensitive Chemical Species; Liyang Zhan*

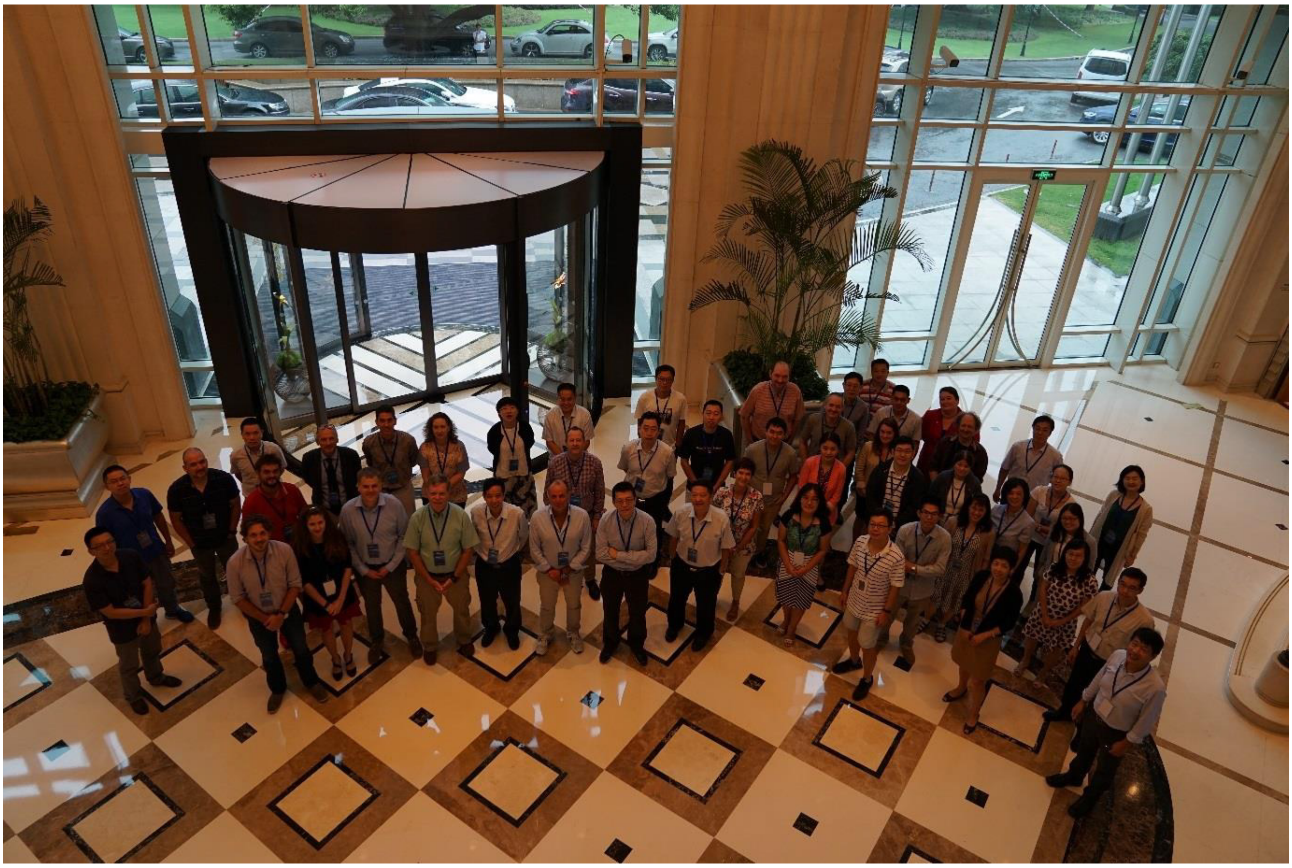
The Southern Ocean (SO) strongly influences climate patterns and the cycling of carbon and nutrients. Changes in the SO therefore have global ramifications. Investigation has revealed that the uptake of carbon by the SO has slowed the rate of atmospheric climate change but caused basinwide ocean acidification; and SO ecosystems are reacting to changes in the physical and chemical environment. Therefore, the Southern Ocean Observing System (SOOS) has addressed a theme on the future and consequences of SO carbon uptake, ocean acidification and their impacts on climate sensitive chemical species biogeochemical cycles as well on global change.

Two fully automatic underway observation systems were developed to measure the surface DMS and $N_2O$ based on laser spectrometer and gas chromatograph, respectively. High resolution DMS and $N_2O$ data were obtained during the 30th and 33rd Chinese National Antarctic Research Expeditions (CHINARE) using these systems. Two large scale DMS sources were identified during 30th CHINARE, which located in the marginal sea ice zone (SIZ) and subtropical front. Strong relationship between DMS and $pCO_2$ in SO SIZ was also founded; the 3-5 % oversaturation of $N_2O$ was observed extensively in the SO during the 33rd CHINARE, though this oversaturation does not seem to be significant, the large area and the high wind speed will in the SO will result a significant $N_2O$ source. Moreover, south of Polar Front (PF), oversaturation of $N_2O$ ~10% correspond with higher salinity in one of our cruise track, suggesting that the possible upwelling of Circumpolar Deep Water may be a source of surface water $N_2O$.

*Variability in chemical properties of the Ross Sea waters: the results of our observations from 1998 to today, Paola Rivaro*

The physical features and the dynamics of water masses together with biological activities control several chemical properties in the Ross Sea, such as dissolved oxygen ($O_2$), nutrients (nitrate, silicate and phosphate), carbonate system parameters (inorganic carbon, total alkalinity, pH and $CO_2$ partial pressure) and trace elements (Fe). The physical and biogeochemical factors influencing the chemical variability in the Ross Sea water masses have been investigated by comparing the data collected during a number of oceanographic cruises. The results show that the distribution of the carbonate system variables in the surface waters is primarily controlled by the biological activities, rather than by physical forcing. However, it is influenced by the sea ice evolution and by the physical properties of the seawater as well; the addition of melting freshwater results in a dilution of the surface total alkalinity and inorganic carbon, consistent with the fact that their distribution is linked to salinity. Shelf–slope exchange processes show short term variability due to different velocities of the gravity currents and tidal currents, and to long- term variability depending on climate variability, influencing the export of $O_2$ and anthropogenic carbon associated with sinking of dense shelf waters. Finally, the observed freshening of the shelf waters could affect their estimated transit time, as suggested by CFC data.

# Appendix 5: Attendees



Photograph of the workshop attendees prior to the start of the first session.

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