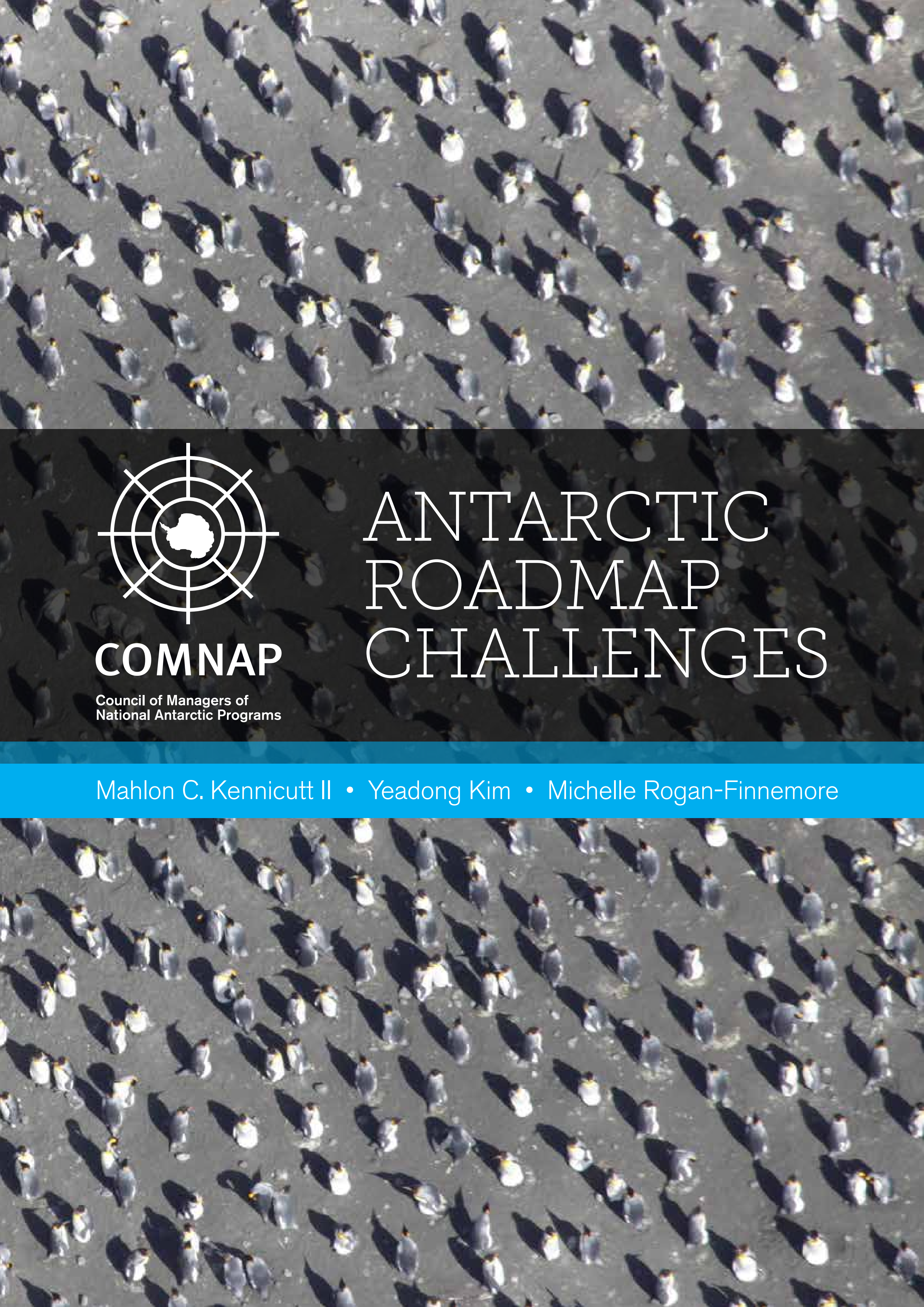

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ANTARCTIC ROADMAP CHALLENGES

Mahlon C. Kennicutt II • Yeadong Kim • Michelle Rogan-Finnemore

ANTARCTIC
ROADMAP
CHALLENGES

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Thala Hills light oversnow transport

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Each of the seven ARC Workshop Writing Group reports was reviewed in final draft form by individuals, chosen for their expertise, who were not involved in the ARC Workshop. The purpose of the review was to provide critical comments that assisted Writing Group leads and COMNAP in making its published outcomes as sound as possible.

We wish to thank the following individuals for external expert reviews of Writing Group reports:

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Contribution of a review does not indicate concurrence with or endorsement of project outcomes and/or products.

Clouds in sky near Jang Bogo Station, July 2015

Photo: KOPRI

FOREWORD

Understanding what research questions will be asked by Antarctic researchers is critical to making the most of our opportunities each year as we travel to the Antarctic region. Knowing what practical, technical, and collaborative activities we need to develop in order to deliver the answers to those research questions is therefore also critical, and that makes the Antarctic Roadmap Challenges (ARC) project an important one.

Through the SCAR Horizon Scan process researchers took the opportunity to think about what the absolutely critical research questions would most likely be for the next decade and beyond. The ARC project was the next step. ARC is an opportunity for the science support community to look across all those critical questions and think about what the necessary infrastructure, technologies, energy requirements, personnel skills and, importantly, funding requirements might be in relation to such research questions – what will be needed in order to deliver critical research outcomes such as those identified in the Horizon Scan process.

While scientists and the science support experts may well be individuals in two separate communities – one represented by SCAR and the other by COMNAP – in fact, neither can operate in the Antarctic without the other. It takes a strong science community and a strong science support community working together to deliver a country's Antarctic science goals and priorities, and it takes government support to fund such expensive science.

When communities work together to understand Antarctic challenges, we can reduce risk, increase our chances of success, and deliver our countries' science priorities in an efficient and cost-effective manner. The goal of the ARC project is not to tell governments what research to do or to support; the goal of the ARC project is to contribute to our understanding of the technical and practical challenges associated with future Antarctic science. COMNAP is the only organisation that can explore such practical and technical challenges in a non-political, collaborative environment, and so we are delighted to be involved in this process.

COMNAP as an organisation strongly supports increased international collaboration in science and science support and recognises that many large-scale, multidisciplinary research projects would not have been possible without collaborative multinational efforts from COMNAP Member national Antarctic programmes. The ARC project will also help us identify likely future international collaborative needs so that we, as national Antarctic programmes, can focus our efforts as best we can in order to be successful.

I want to personally thank the co-conveners, the Project Manager, and all those who responded to the surveys or contributed time and expertise to the workshop or to any stage in the project. If you are like me, you are a passionate "Antarctican". And, if you are like me, you will recognise that we have an opportunity here to contribute to something that is important to our communities' future.

Kazuyuki Shiraishi

Professor Kazuyuki Shiraishi
Director General
Japan's National Institute of Polar Research
COMNAP Chair

FOREWORD

While the southern Polar Region of our planet is often perceived as being remote and distant from people's daily lives, events there are widely reported in the media, attracting wide public interest. As one of the greatest remaining wildernesses on the planet, the region inspires a sense of awe and wonder.

In contrast, the dramatic developments being observed instill a foreboding of what the future holds as our planet rapidly changes and warms. Knowledge to be gained in the Polar Regions provides exceptional insights into some of society's most pressing concerns, including, but not limited to, climate change (global warming), sea level rise, and threats to the planet's biodiversity. Building on nearly six decades of science and research dating back to the International Geophysical Year (1957–1958), the promise of future knowledge and insight to be gained by studying and understanding the Antarctic region has never been greater. Earth System Science recognises that the planet is a network of interconnected physical and living subsystems and that perturbations in one region reverberate throughout, having consequences for, and invoking responses in, other regions of the system. How these complex systems may respond in the future to global events and human activities is incompletely understood at best and often unknown.

Over the decades it has become increasingly apparent that the Polar Regions are critically important elements of the planetary system. Earth's Polar Regions not only respond to global change but in many instances are the epicenter and/or the origin of important processes that control or modulate global water, heat, energy, and chemistry budgets. The Polar Regions house one-of-a-kind sediment, rock, ice, and fossil evidence of the history of our planet, from "deep-time" to recent climate oscillations, which provides a matchless window on possible futures. The evolution and adaptations of Antarctic organisms, from the molecular to the population/ecosystem level, are unique on the planet and are known to be responding to climate change. It is also cited that a wide spectrum of human pressures on the region are increasing in intensity and complexity. The Earth System and how it has and will respond to anthropogenic stressors cannot be fully understood or predicted without understanding the Polar Regions and their teleconnections to lower latitudes. Our understanding of change in the Antarctic region, and why it is happening, is important to informing the global debate about the trajectory of our planet's environment and how decisions by humans can effect and alter future outcomes.

In recognition of the growing importance of Antarctic science and research in global debates, the international community came together in an unprecedented effort to define the highest-priority scientific questions that can be uniquely addressed by studying the region. In addition, the community assessed what it will take to enable the research necessary to realise the promise of Antarctic science at the dawn of the twenty-first century. The initial step was the first Scientific Committee on Antarctic Research (SCAR) Antarctic and Southern Ocean Science Horizon Scan, which identified the highest-priority scientific questions that researchers aspire to answer (Kennicutt et al., 2014 a, b). The Horizon Scan was followed by the Council of Managers of National Antarctic Programs (COMNAP) Antarctic Roadmap Challenges (ARC) project to determine the steps necessary to enable the community to conduct research that will answer the critical questions. Both of these exercises widely consulted the international Antarctic community to define a collective vision of one possible path to the future and what it will take to fully realise the promise of Antarctic research.

This document describes the process and the outcomes of the COMNAP ARC project in terms of enabling technologies, essential access, and the infrastructure and logistical support required to answer the questions identified by the SCAR Science Horizon Scan.

It was my pleasure to act as Project Manager for the SCAR Horizon Scan project and as Co-convener, along with Dr. Yeadong Kim, for the COMNAP ARC project.

Mahlon C. Kennicutt II

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The sky above Concordia Station, Antarctica

Photo: E. McDonald, IPEV

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Photo mosaic image of Antarctica

SUMMARY

The Council of Managers of National Antarctic Programs (COMNAP) initiated, organised, and managed the Antarctic Roadmap Challenges (ARC) project. The ARC project's goal was to identify the critical requirements to enabling and delivering key science objectives through research in and from the southern Polar Regions in the next two decades. Critical requirements were determined based on a careful and thorough analysis of the 80 highest-priority scientific questions previously presented in the "Roadmap for Antarctic Science" that had been developed by the SCAR Antarctic Science Horizon Scan project. ARC would not have been possible without the outcomes of the SCAR Horizon Scan and without collaboration with SCAR. The ARC and Horizon Scan projects provide important information about possible future directions in science and support, which will inform future decision-making by the international Antarctic community.

ARC and the Antarctic Science Horizon Scan projects conducted open, on-line surveys and assembled meetings of invited experts. Peer-review was utilised to ensure robust conclusions and to increase participation. The "Roadmap for Antarctic science" can be followed only if several major challenges are addressed: 1) the accessibility and development of critical technologies; 2) provision of essential and extraordinary logistics capabilities; 3) the availability of vital supporting infrastructure to provide access to the region; 4) enhanced and new models for international cooperation and partnerships; 5) the development of strategies to provide and meet a wide range of energy demands; 6) ensuring stable and sustained funding; and 7) the development and availability of essential human skills and resources. The ARC project focused on addressing the first three challenges (technologies, logistics, and infrastructure and access) and commented on the key role of the fourth (international cooperation).

The ultimate ARC activity was a workshop of invited experts that considered the results of the surveys, white papers by interested parties, and existing planning and strategic documents by various sub-communities. The workshop attendees were organised into Writing Groups based on the Horizon Scan question clusters. Each Writing Group followed a guideline document and answered a series of questions as the basis for discussions and drawing of conclusions. This report is a synthesis of these Writing Group reports, which are also provided verbatim as appendices.

RESULTS AND CONCLUSIONS

The key findings of the ARC project can be broadly described as "cross-cutting (community-wide)" and "science topic-specific" requirements. The overarching cross-cutting items are those technologies, access, infrastructure, and logistics requirements that were identified as a high priority across all science topics. In regards to technologies, the parameters to be measured were not explicitly considered, as these (e.g. key variables) are the focus of expert groups elsewhere. Nevertheless, the target attributes will be critical to developing technologies such as observatories and sensors. Antarctic scientists must be vigilant in keeping abreast of developments in mainstream science – particularly on the technological front. It is a challenge to bring to bear what others have learned elsewhere, and a failure to do so diminishes the justifications for Antarctic science.

"Cross-Cutting" Technologies

The highest-priority "cross-cutting" technological requirements were (order does not imply priority):

- Improved and expanded observing systems and sensor arrays that are interoperable, autonomous (can be sustained during long-term [years] deployments continent- and ocean-wide), are capable of meeting and managing growing and varied power demands, are stable and able to maintain long-term calibrations, and are capable of gathering and streaming or storing large amounts of data at finer and finer temporal and spatial scales.
- Advanced data analysis and computational capabilities based on the latest and developing cyber-information and communications technologies and high-performance computing.
- Enhanced satellite remote sensing capabilities with expanded and improved sensors, coverage, and availability that can provide integrated, synoptic region-wide measurements and that can capture diverse types of data.
- Improved coupled Earth System Models that integrate a wide variety of sub-system models and observations, and that include capabilities to handle diverse "big data" sets that will be produced by improvements in bandwidth and transmission capacities.
- Improved retrieval capabilities for all types of samples, including "clean" and "*in situ*" capabilities as well as the ability to provide ground-truth for remote and autonomous sensing arrays.

"Science Topic-Specific" Technologies

The ARC project identified technological requirements that were "science topic-specific". In most instances the cross-cutting technologies above will benefit, and are essential to, the more specific requirements listed below, and only the highest-priority "other" technologies are presented. In many cases finer details about the cross-cutting requirements are provided by the science topic-specific needs.

Key "science topic-specific" requirements were:

Antarctic Atmosphere and Global Connections
Continuous measuring sensors and remote weather stations with expanded and robust sensor arrays, technologies for "smart" (unattended) deployment, and improved models are some of the highest-priorities for the atmospheric sciences. The Antarctic community needs to more fully engage with national space agencies to ensure their needs are represented in planning efforts. Scientific advancement of Antarctic atmospheric sciences in the next two decades will be critically dependent on the improved exchange of people and information – including improved logistics coordination, technology transfer, and dissemination, and the availability and coordination of databases.

The Southern Ocean and Sea Ice in a Warming World
An overarching goal of ocean sciences research is much greater automation of measurements and lessening dependency on moored platforms to perform field work. Improved underwater and under-ice navigation and positioning are needed to accurately emplace autonomous platforms. Animal-based and other sustainable and deployable technologies need to be made more widely available and less expensive.

The Ice Sheet and Sea Level
The integration of models with a wide range of in-field observations will be critical to developing the next-generation ice-sheet models capable of describing and predicting realistic ice flow. Ice-sheet flow

is critically affected by basal processes and ice rheology, both of which are not well described in models. To obtain the necessary observations, sampling of the subglacial environment and en-glacial environments is needed, including more-detailed geophysical imaging and mapping of the ice sheet and wider use of remotely deployed expendable instruments. Application of existing private sector 3-D seismic techniques would provide transformative insights into basal processes and ice structures.

The Dynamic Earth Beneath Antarctic Ice

Deployment of sensor arrays capable of acquiring continuous year-round data, as part of a sensor network capable of transmitting high volumes of data over long distances, is needed. These will require improvement of existing technologies for ice borehole drilling, sampling of subglacial sediments and rocks, and ocean drilling.

Life on the Precipice

The key technologies for the life sciences include improved and more-robust sensors with automated calibration, sensor networks, and higher sensor resolution for monitoring the *in situ* structure and function of living systems. High-volume automated multi-omic platforms for phylogenetic and functional analysis of multiple large-scale meta-omic sample sets, including automated *in situ* meta-genomic analysis and integrated bioinformatics analysis, are critical.

Near-Earth Space and Beyond – Eyes on the Sky

Next-generation large single-dish telescopes will require novel designs in order for the telescopes (including optical/infrared telescopes deployed to the interior of Antarctica) to be transportable to remote locations. A broad range of geophysical phenomena, spanning magnetic and geographic latitudes from the sub-aurora zone to the polar caps, at altitudes from the troposphere to near-Earth space, are observable but will require the development of autonomous measurement systems that can operate unattended for long periods in severe environments.

Human Presence in Antarctica

New and better sampling and handling technologies and better sensing and surveillance technologies and tracking systems are needed, including autonomous tracking devices and smart technologies. For many of the humanities- and social science-focused questions access to information is a critical limiting factor.

The Status of Critical Technologies

Approximately one third of the required technologies were identified as currently available but available only to a select set of scientists. Other technologies were considered to be currently available in one form or another but with the potential to benefit from improvements. In other instances, new technologies are required. Advancements in a number of technological areas will most likely come from outside of the Antarctic community and the challenge is to apply the latest developments in these areas to Antarctic science. Many of the required technologies are under continual improvement, and advances will incrementally occur over a number of years. Technological advances are critical to answering many high-priority scientific questions and can fundamentally change what questions are addressable, and even what scientific questions can be asked. The rate at which technological challenges will be addressed is in large measure controlled by the magnitude and rate of investments and the ability of the community to focus efforts on highest-priority needs.

Access, Infrastructure and Logistics

The majority of Antarctic research is field-based and will continue to be so for the foreseeable future, and access is often a critical limiting factor in conducting research. While many of the identified access needs can be met by the national Antarctic programmes, greater access is required over longer periods of the year. The preponderance of observations and measurements to date, other than those by satellite-based sensors and autonomous observatories, have been made during the austral summer, due to the difficult operating environment during other times of the year. Many scientific questions will require year-round continent- and ocean-wide access. High-priority areas for expanded access include coastal areas (including beneath ice of all kinds – floating and grounded), the interior of Antarctica (including deep field camps), and the Southern Ocean. Three of the seven science topics noted the importance of access to West Antarctica.

The optimal locations for measurements, experiments, and observations may be remote from permanent stations. Greater geographical access without additional permanent stations can be provided by the deployment, servicing, and retrieval of automated observatories and platforms, the development of modular and relocatable laboratories/facilities, temporary stations, and expeditionary-style field programmes. An ability to rapidly deploy teams of scientists to rapidly changing regions to collect benchmark observations was seen as a priority as well.

The Costs

The costs associated with provision of technologies and support requirements vary over a wide range. At the lower-cost end of the spectrum (tens of thousands to hundreds of thousands of US dollars) is advancement of data-handling and analysis techniques. At the higher end of the cost spectrum (tens of millions to hundreds of millions of US dollars) is permanent infrastructure, such as ships and stations and dedicated satellite missions. Major technological needs may require pooling of resources for greatest effect. Partnerships, sharing of facilities and technologies, and coordination of efforts maximise return on investments and reduce impacts on the environment. The cost analyses indicated a wide range of opportunities for scientists and nations to contribute to the collective effort, within resource limitations and national interests.

International Collaboration

The ARC project reaffirmed that no one country has the wherewithal to simultaneously pursue all aspects of the highest-priority Antarctic science. Continuing and enhanced cooperation in the spirit of the Antarctic Treaty remains a high priority and an ever increasing financial reality for national programmes. In a number of critical areas, such as satellite remote sensing, development of sensors and automated and robotic platforms, computing and information technologies, and advances in power technologies, it is expected that advances will occur outside of the Antarctic community. If it is to remain relevant, the community needs to be ever vigilant and must capitalise on advances in mainstream science through their application to the research conducted in the Antarctic. The availability and production of “big data” are a modern scientific phenomenon that has wide-ranging implications, and this massive flow of data can be optimally utilised only by applying the latest technologies in information, communications, and computation. The remoteness of the Antarctic introduces special challenges to addressing these issues.

Concluding Remarks

The ARC and Antarctic Science Horizon Scan projects have provided a unique and rare opportunity for the international Antarctic community to come together to speak with one voice. In a world of competing demands on national resources it is more critical than ever that the Antarctic community communicate to funders and the public on why what we do is important to larger global debates. Through these two projects, the community has collectively laid out an ambitious vision of one possible path to the future. ARC points the way to what it will require to enable the far-reaching scientific agenda envisioned. Ultimately, success will be dependent on national investment in technological advances, provision of greater access region-wide and year-round, and the availability of logistics and infrastructure that allows researchers to do their best work where it must be performed. This vision reaffirms that the underpinning philosophy of Antarctic science remains international cooperation, coordination, and partnerships. It has never been more important that the global Antarctic community find new ways to work together that leverage national assets and investments in Antarctica.

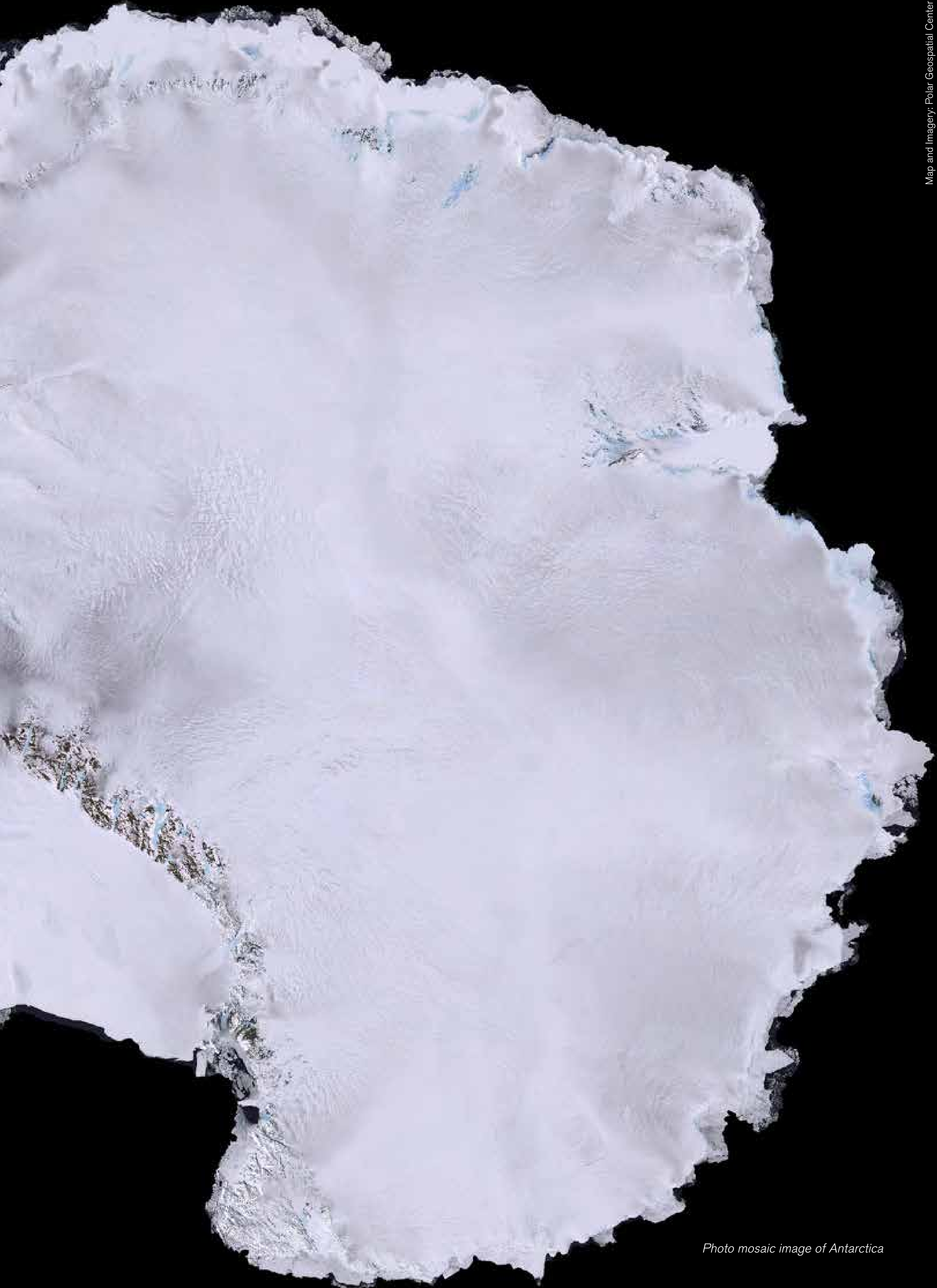


Photo mosaic image of Antarctica

Map and Imagery: Polar Geospatial Center

Scientific research activity

Photo: KOPRI

INTRODUCTION

The conduct of scientific research in the Antarctic region requires substantial and sustained investments by governments to meet the challenges of working in one of the most remote and extreme environments on Earth. In 2014, the first SCAR Antarctic and Southern Ocean Science Horizon Scan assembled world-leading Antarctic scientists, policy makers, leaders, and visionaries to identify the most important scientific questions that will or should be addressed by research in and from the Antarctic over the next two decades. The outcome was agreement on 80 of the most important Antarctic research questions, laying out an ambitious scientific "roadmap" for the next 20 years (Kennicutt et al., 2014 a, b).

Effectively navigating the "Antarctic science roadmap" will require addressing a range of challenges. COMNAP then led the second stage of the process, initiating the Antarctic Roadmap Challenges (ARC) project. The ARC project focused on answering this question: "How will national Antarctic programmes meet the challenges of delivery of Antarctic science in the next 20 years or more?" As the entities that fund and support Antarctic science, national Antarctic programmes will face practical and technical issues as the Antarctic science roadmap is enabled over the next two decades. As part of the ARC project, wide community involvement and advice were solicited to assist in translating high-priority Antarctic research questions into actionable requirements for critical supporting technologies, access, infrastructure, and logistics.

From the SCAR Horizon Scan, COMNAP identified seven practical and technical challenges related to the roadmap. The COMNAP ARC project focused on three of the seven challenges identified:

CHALLENGE 1: TECHNOLOGY

"Innovative experimental designs, new applications of existing technology, invention of next-generation technologies and development of novel air-, space- and animal-borne observing or logging technologies will be essential." (Kennicutt et al., 2014b)

Science has historically been advanced by improvements in technology – notable is the emergence of space-based technologies over the last six decades. New designs, instrumentation, sensor technologies (from micro- to macro-scale), and "clean" technologies will continue to be required as scientists probe ever-more complex questions. Technological advances not only support ongoing science but also may limit what science can be done and, in some instances, change the scientific questions being asked (for example, genomics has revolutionised ecology). Marine research requires technologies that allow for exploration of the benthos, the water column, areas below ice shelves, and interfaces between water, ice, and the atmosphere. This will require improvements in long-duration buoys and associated sensors, remotely operated and autonomous (robotic) underwater vehicles, and miniaturised instruments deployable on animals and other platforms.

CHALLENGE 2: EXTRAORDINARY LOGISTICS REQUIREMENTS (ACCESS)

"Future research in Antarctica will require expanded, year-round access to the continent and the Southern Ocean." (Kennicutt et al., 2014b)

Antarctic logistics requirements are complex and challenging. The geographic isolation, the extreme physical conditions (weather and darkness), the expense, and the implementation of policy and reporting requirements make planning and logistics complicated and demanding on people, resources, and time. Intercontinental air routes are limited, though well-established, but future science requirements critically depend on an expansion of intra-Antarctic flights and ground-traversing capabilities, including expanding into

"Antarctic science has global consequences"

– *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* (National Academies of Sciences, Engineering, and Medicine, 2015)

"Antarctic and Southern Ocean scientific research has produced many important and exciting scientific advances. Spanning oceanography to tectonics, glaciology to atmospheric chemistry, microbiology to astrophysics—the extreme Antarctic environment provides unique opportunities to expand knowledge about how the planet works and even the very origins of the universe. Research on the Southern Ocean and the Antarctic ice sheets is becoming increasingly urgent for understanding the future of the region and its interconnections with and impacts on many other parts of the globe."


Photo: AWI

Balloon launch from Neumayer III Station

Photo: CSIC-UTM-BAE, national Antarctic programme of Spain

Back home to Spanish Juan Carlos I Station, Livingston Island

under-studied but scientifically interesting regions. Future research will be advanced by data gathering and sample retrieval from atmospheric, sub-glacial, and deep-sea environments that will require expanded logistics capabilities. Science that is achievable using improved remote sensing capabilities will introduce new challenges. Not only will aircraft, satellites, balloons, and Unmanned Aerial Vehicles (UAVs) continue to be used as platforms for science, but usage will increase. Research vessels, ice-breakers, and cargo ships provide important logistics capabilities. Such vessels are expensive to build, operate, and maintain, requiring long-term and substantial investments by nations. Deployment of scientific equipment to Antarctica requires years of advance planning and includes consideration of contingencies such as redundancy in systems and supplies.

CHALLENGE 3: INFRASTRUCTURE

"Antarctica and the Southern Ocean occupy a vast territory, much of which is inaccessible during Austral winter months. Even during summer months the conditions prove challenging ... infrastructure is essential to survival and is vital to the conduct of science. Two kinds of infrastructure can provide opportunities to advance scientific research in Antarctica: physical systems infrastructure, including transport, and cyber-infrastructure." (National Research Council, 2011)

The original expansion of physical systems infrastructure on the continent began in 1957–58 in support of the International Geophysical Year. Upgrades, refurbishments, and new stations and related facilities have occurred in the intervening years, especially during the International Polar Year 2007–2008. Infrastructure implies a "permanence" and does not include numerous temporary field facilities established for finite periods to support specific activities or science programmes. There are vast regions of the Antarctic that remain virtually unexplored, except by space-borne sensors, where there has been no direct human presence. However, high-priority scientific questions will require extensions into areas not now occupied or accessible. These environments include remote land areas, sub-ice locations, beneath ice shelves, and the deep sea. Requirements for many of the astronomy-related programmes will entail winter-over infrastructure and long-term observing programmes. For example, the discovery of ozone depletion and the subsequent long-term data set collection would not have been possible without instrumentation at a permanent station. Do we continue to build infrastructure in Antarctica, and, if so, in what form and where? It can be envisioned that future programmes will require simultaneous presence across the continent and ocean – how will these nodes of exploration be established and coordinated? Environmental concerns remain paramount and efforts to reduce the human footprint in the Antarctic have found wide support.

THE PROCESS

For both the Horizon Scan and the ARC project, a series of community-based activities were conducted, culminating in two gatherings of experts and experienced Antarctic scientists and engineers, logisticians, national programme directors and managers, policy makers, and technologists. Surveys were constructed using Qualtrix© software and were open to the global community online. The Horizon Scan outcomes are reported as a Comment in *Nature* (Kennicutt et al., 2014a) and in *Antarctic Science* (Kennicutt et al., 2014b).

ANTARCTIC SCIENCE ON THE HORIZON

Collective international planning has a long history in Antarctic science, founded in the Antarctic Treaty of 1959 and four International Polar Years. Dating to the 1800s, Polar Years have been planned at thirty-to-fifty-year intervals. International cooperation is a cornerstone of Antarctic science and reflects the international spirit espoused by the Antarctic Treaty, which sets the geopolitical framework for consultative management of the region south of 60° south. Other conventions and agreements have established the framework for science conducted in the southern Polar Regions.

The most recent International Polar Year (2007–2008) laid out a comprehensive framework of hundreds of programmes and projects that promoted international cooperation, data sharing, and optimal use of science support activities. However, Polar Years are infrequent. In order to provide a more regular opportunity for collective international planning the Horizon Scan methodology was adopted, adapted, organised, and managed by SCAR. It has been described thus:

> A horizon scan is a priority-setting method that systematically searches for opportunities, which are then used to articulate a vision for future research directions. The scan methods of Sutherland et al. (2011, 2013) were customized to the requirements of Antarctic and Southern Ocean science, which is region-based and includes a wide range of scientific disciplines and research topics. The scan process was designed to be inclusive and transparent. There were opportunities to contribute scientific questions and to nominate experts to attend a gathering of experts to prioritise questions. A website was established, which served as a resource and a record of the scan (http://www.scar.org/horizonscanning/). (Kennicutt et al., 2014b)

The first Antarctic Science Horizon Scan systematically identified the most important, highest-priority scientific questions that the global science community should aspire to answer over the next two decades and beyond. The Scan process was inclusive and encouraged wide community participation. The Scan outcomes were intended to inform effective alignment of financial, human, logistical, and infrastructure resources with the requirements for future Antarctic science. The Horizon Scan activity solidified existing partnerships, forged new relationships, mentored early career scientists, and communicated the importance of Antarctic science to a wide audience. The primary output of the Horizon Scan was the 80 highest-priority Antarctic and Southern Ocean scientific questions from nearly 1000 ideas generated by the community (Kennicutt et al., 2014a). Once identified, the highest-priority scientific questions were organised into seven thematic clusters – many questions were cross-cutting and interdisciplinary.

The seven clusters were (see Table 1):

1 and 2) "Antarctic Atmosphere and Global Connections" and "The Southern Ocean and Sea Ice in a Warming World" – Questions that consider the behaviour of the Antarctic atmosphere, ocean, and sea ice as drivers of global climate, and that consider these features' connectivity to the Earth system, in order to improve climate predictions.

3) "The Ice Sheet and Sea Level" – Questions to lead to knowledge that will improve decadal- to century-scale forecasts of sea level, and more accurately portray "ice sheet–ice shelf" dynamics and sensitivities to atmospheric and oceanic forcing in models.

4) "The Dynamic Earth Beneath Antarctic Ice" – Study of the deep-time history of Earth to improve understanding of plate tectonics, the evolution of life, and the history of planetary ice, and to validate climate, ice-sheet and sea-level models.

5) "Life on the Precipice" – Exploration to better understand the interplay of evolutionary adaptation and ecological drivers crucial to forecasting biotic responses to change, and to advance life sciences knowledge through censuses and process studies.

6) "Near-Earth Space and Beyond – Eyes on the Sky" – Observing space from Antarctica to develop unique insight into the origins and structure of the universe, the nature of the Dark Universe, the evolution of galaxies, the birth of stars, and the dynamics of the ionosphere, and to identify planets capable of sustaining life.

7) "Human Presence in Antarctica" – Research to better understand the impacts of humans in Antarctica, and the challenges this presents to governance regimes.

ENABLING ANTARCTIC SCIENCE

The goal of the ARC project was to translate the 80 highest-priority Antarctic and Southern Ocean scientific questions identified by the community via the Horizon Scan into technological and operational needs. The ARC project was designed to provide specificity to the highest-priority technological, access, logistic, and support needs that the community judged would provide the greatest scientific return on investments in the context of answering the highest-priority questions. Effort was made to achieve a consensus, collective view, and to prioritise among the many possible options and needs. The objective of the ARC project was to communicate to, and raise awareness among those who fund science, the technological advances and logistical support that are essential to delivering and enabling international Antarctic research over the next 20 or more years. The ARC project included two online surveys of the community and a workshop of experts from 23 to 25 August 2015 in Tromsø, Norway. ARC Survey 1 addressed highest-priority technological needs, and over 400 responses were received (see Appendix 1). ARC Survey 2 addressed the feasibility and cost of the highest-priority technological and logistical needs identified in Survey 1 and received more than 250 responses (see Appendix 2).

Experts were assembled at the Tromsø workshop to consider a series of solicited and unsolicited white papers submitted by a range of Antarctic science communities, ARC survey results, summaries from the Horizon Scan, and other planning and strategic documents that assessed future Antarctic science technology and logistics requirements. There were 60 participants in the workshop, which included logistics and operations experts, experienced Antarctic scientists and researchers, and national Antarctic programme personnel from 22 countries. The workshop was structured around the seven Horizon Scan science question clusters and included five Writing Groups that were assigned co-Leads (one scientist/researcher and one national Antarctic programme expert) and a scribe to record deliberations. Writing Group members were assigned based on expertise and the need to ensure broad disciplinary and geographic representation within groups.

Prior to the workshop, Writing Groups were provided with a detailed "Guide" to ensure preparation beforehand. Each Writing Group was provided with the same standard forms, which contained a series of questions. By answering the questions, the Writing Groups methodically identified the highest-priority technological needs, including the current status of development and availability, where geographically the technologies would be utilised, at what temporal scales and frequencies the technologies would be employed, and how broadly applicable the technologies were for answering the highest-priority scientific questions. Secondly, Writing Groups considered the access, logistics, and infrastructure requirements to deliver the science in terms of feasibility, including cost and benefit as judged by expected scientific return on investment. Each Writing Group completed the forms and agreed on final report wording. The draft reports were reviewed by external experts who had not been at the workshop, and the reports were then revised to a final version.

In addition to the basic questions regarding requirements, the Writing Groups were asked to identify those needs that are so complex, require such long-term investments to achieve, and/or have such associated cost that realistically they can be met only (or best) by international coordination, planning, and partnerships. Writing Groups were also asked to identify major trends (changes) in logistics, access, and infrastructure requirements that will impact long-term, strategic alignment of international capabilities, resources, and capacity. In a concluding section the Writing Groups were asked to summarise the most important "take-home messages" for those that fund and support Antarctic research. The final Writing Group reports were analysed to discern the highest-priority needs that support the broadest swath of the Antarctic community and have the greatest potential for optimal scientific return in the next 20 years. In Appendix 3 these findings are reported and the bases for the conclusions drawn are summarised in detail for completeness. The wording of the final versions was agreed to by all participants in each particular group. They reflect the personal views of the participants and have not been agreed to by all participants in the workshops, nor by SCAR or COMNAP.

Photo: NASC photo archive

Glaciological research

Antarctic Atmosphere and Global Connections

“Changes in Antarctica’s atmosphere alter the planet’s energy budgets, temperature gradients, and air chemistry and circulation. Too little is known about the underlying processes. How do interactions between the atmosphere, ocean and ice control the rate of climate change? How does climate change at the pole influence tropical oceans and monsoons? How will the recovering ozone hole and rising greenhouse gas concentrations affect regional and global atmospheric circulation and climate?”

The Ice Sheet and Sea Level

“The Antarctic ice sheet contains about 26.5 million cubic kilometers of ice, enough to raise global sea levels by 60 meters if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO_2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown.”

The Southern Ocean and Sea Ice in a Warming World

“The Southern Ocean has important roles in the Earth system. It connects the world’s oceans to form a global system of currents that transfers heat and CO_2 from the atmosphere to the deep ocean. Nutrients carried north support the base of the ocean’s food web. The ocean is becoming more acidic as CO_2 dissolves in sea-water, and cold southern waters will be the first to exhibit impacts. How will climate change alter the ocean’s ability to absorb heat and CO_2 and to support ocean productivity? Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? Why have the deepest waters of the Southern Ocean become warmer and fresher in the past four decades? Sea ice reflects and filters sunlight. It modulates how heat, momentum and gases exchange between the ocean and atmosphere. Sea ice formation and melt dictate the salt content of surface waters, affecting their density and freezing point. What factors control Antarctic sea ice seasonality, distribution and volume?”

The Dynamic Earth Beneath Antarctic Ice

“Glimpses of the past from rock records collected around the continent’s margins suggest that Antarctica might look markedly different in a warmer world. But rocks from the heart of the continent and the surrounding oceans have been only sparsely probed. Responses of the crust to, and the effects of volcanism and heat from Earth’s interior on, overlying ice are largely undescribed. We know little about the structure of the Antarctic crust and mantle and how it influenced the creation and break-up of super-continents. Ancient landscapes beneath ice reveal the history of interactions between ice and the solid Earth. Geological signatures of past relative sea level will show when and where planetary ice has been gained or lost. We need more ice, rock and sediment records to know whether past climate states are fated to be repeated.”

Life on the Precipice

“Antarctic ecosystems were long thought of as young, simple, species-poor and isolated. In the past decade a different picture has emerged. Some taxa, such as marine worms (polychaeta) and crustaceans (isopods and amphipods) are highly diverse, and connections between species on the continent, neighboring islands and the deep sea are greater than thought. Molecular studies reveal that nematodes, mites, midges and freshwater crustaceans survived past glaciations. To forecast responses to environmental change we need to learn how past events have driven diversifications and extinctions. What are the genomic, molecular and cellular bases of adaptation? How do rates of evolution in the Antarctic compare with elsewhere? Are there irreversible environmental thresholds? And which species respond first?”

Near-Earth Space and Beyond – Eyes on the Sky

“The dry, cold and stable Antarctic atmosphere creates some of the best conditions on Earth for observing space. Lakes beneath Antarctic glaciers mimic conditions on Jupiter and Saturn’s icy moons, and meteorites collected on the continent reveal how the Solar System formed and inform astrobiology. We have limited understanding of high-energy particles from solar flares that are funnelled to the poles along the Earth’s magnetic field lines. What is the risk of solar events disrupting global communications and power systems? Can we prepare for them and are they predictable?”

Human Presence in Antarctica

“Forecasts of human activities and their impacts on the region are required for effective Antarctic governance and regulation. Natural and human impacts must be disentangled. How effective are current regulations in controlling access? How do global policies affect people’s motivations to visit the region? How will humans and pathogens affect and adapt to Antarctic environments? What is the current and potential value of Antarctic ecosystem services and how can they be preserved?”

Table 1: The seven thematic Horizon Scan clusters, with summaries

Stadia surveying

Photo: AARI/RAE

RESULTS AND CONCLUSIONS

While surveys and discussions were organised around the Horizon Scan scientific clusters and disciplines, major cross-cutting technological requirements emerged. In this section, such generalities are summarised first and specifics are then discussed as the details are often science-question or cluster dependent. It is also noted that the design of experiments will dictate the finer details of the technological needs and expert advice will be important in implementing recommendations.

CROSS-CUTTING TECHNOLOGIES

In the surveys and during workshop discussions, many cross-cutting technological requirements were identified. These requirements can be broadly characterised as:

- advanced observing systems, sensors, and platforms (automation/robotics);
- improved models of all types;
- new and improved satellite sensors, including appropriate coverage and availability;
- sampling technologies, including ground-truth for sensors and automated devices; and
- data accessibility.

Observing Systems and Sensors

Observing systems and sensors were broadly interpreted to include a wide range of technologies, from those used within the solid Earth to those used sub-ice and within-ice, to those used on satellites, balloons, aircraft, and animals. The critical environmental properties and/or variables to be sensed are highly dependent on the scientific questions being asked, have been widely discussed by various communities (e.g. key variables), and are described in more detail below. Increasingly, observatory platforms need to be nodes capable of supporting a diverse array of sensors (interoperable) that support many differing disciplines, to allow interdisciplinary, synoptic collection of data. Improved observing platforms and technologies must be capable of operating autonomously and be provided power in a way that allows for sustained, long-term (months to years) deployment continent- and ocean-wide at all times of the year. The range and capacity of autonomous vehicles need improvement, including provision of the necessary bandwidth and continuity in data communications to allow data collection and transfer in and from remote areas. For example, year-round monitoring of weather in the Southern Ocean through such means is vital to understanding of global connections and to supporting operational forecasting. Ice-tethered platform/profilers, sea-ice buoys, drifters, and moorings are needed to support long-term sea-ice observations. Buoy networks of sensors deployable in the deep ocean for long periods of time (years) are needed to trace sea water properties and chemistry. Autonomous observatories must be able to support combinations of interoperable physical, chemical, and living system sensors that are capable of automated calibration and high data-collection rates in space and time. Robotic (controlled and autonomous) multi-purpose systems and vehicles for continuous and long-term *in situ* process monitoring that can collect and return samples for ground-truth are needed. Improvements in power supplies are a core challenge that cross-cuts the many wished-for observatory platform capabilities. It is likely that advances in power technologies will come from beyond the Antarctic community.

Greater automation across the board – through the use of Automated Underwater Vehicles (AUV), Unmanned Aerial Systems (UAS), drones, and gliders – will be a hallmark of twenty-first century Antarctic science. Deployable automated sensor technologies will need to collect data at finer and finer spatial and temporal scales and must be deployable on a wide variety of platforms, from *in situ* to satellites. Increased investment in survey capabilities/tracking of human and vehicle activities related to anthropogenic impacts is needed to minimise disturbances and reduce the human footprint.

> “Antarctic science integrated observation system”
>
> ***– More and Better Science in Antarctica through Increased Logistical Effectiveness: Report of the US Antarctic Program Blue Ribbon Panel*** **(2012)**
>
> “The lack of geographically extensive, long-term observation records and a paucity of observations south of the peninsula and McMurdo regions are … limiting the ability to reduce uncertainties in climate change models. … [A] comprehensive, coordinated, and networked interdisciplinary observing and prediction system that would encompass all the major elements of the Antarctic environment—the atmosphere; terrestrial, marine, and subglacial ecosystems; permafrost; ice shelves; ice sheets; and subglacial habits of the interior as well as the ocean and sea ice [is needed]. Thus, observational systems with the latest technology to gather atmospheric, ice, and ecological information will be necessary to provide the means to assess ice, biotic, and meteorological changes in the relatively unexplored interior of the continent as well as other areas of the continent and Southern Ocean …
>
> An effective observing system approach will require enhanced access to the interior of the continent for timely data collection (and subsequent transmission), maintenance, and support as well as other logistics services. Many research topics will span the entire continent in an integrated fashion and are not specifically tied to … major … stations. … [C]apability in Antarctica will need to evolve to enable continent-wide, long-duration, multi-disciplinary research …
>
> … [P]lanning, designing, and implementing an Antarctic Observing Network and meeting the challenge of successfully colocating a diverse set of low-power research instrumentation and supplying reliable, renewable power along with necessary communications [with] year-around … capability in Antarctica will need to evolve to enable continent-wide, long-duration, multi-disciplinary research, including partnering with and benefiting from … national programs seeking to contribute to such an endeavor.”

Oceanologists at work

Photo: A. Kidawa, national Antarctic programme of Poland

Antarctic Autonomous Polar Observing Systems

– Autonomous Polar Observing Systems Workshop Report (2010)

“Polar landmasses, ice sheets, and sea ice provide unique observing platforms for research in many fields, including geodesy, meteorology, seismology, glaciology, and space physics. Areas of high interest include ice sheet stability and its effects on sea level rise, ice shelf melt and breakup, sea ice variability, glacial/oceanic interactions, the evolution and geophysical state of the mantle and crust, solar wind energy, mass and momentum coupling in Earth’s magnetosphere and upper atmosphere, postglacial and tectonic deformation, and the fundamental processes and evolution of the core and terrestrial magnetic field. … [C]ontinued scientific advances will require coordinated data collection at increasing numbers of locations in order to probe key dynamical processes at the required spatial and temporal scales. Understanding some of these processes requires data-collection systems that can function unattended for several years or longer. … [A] new generation of cost-effective autonomous instruments with improved capabilities and greater sophistication [will be required].

“Development of the necessary power, communication, instrumentation, and packaging/deployment system components can be significantly advanced through expanded and sustained collaborations among the scientific community … [including:]

1) ‘Supersites,’ … where many researchers … share logistics and on-site capabilities, and where support personnel would have the training to meet the needs of multiple science groups.

2) Improved early planning and subsequent coordination of field camps and traverses.

3) [A]n accessible … international database of … polar deployments and … logistical resources.

4) Timely publication … of … ‘best practices’ information …

5) Establishment … of interdisciplinary working groups …

6) …[C]ommunity conferences with … instrumentation consortium participation …

7) [Engagement opportunities] for science and engineering students … ”

Satellite Remote Sensing

Improved satellite remote sensing is needed to make synoptic region-wide measurements. High-volume satellite/microwave bandwidth is essential to integrating diverse data capture for on-site and off-site analysis. Almost all scientific disciplines and themes will greatly benefit from a broader range of sensing capabilities, and in many instances the required spatial and temporal coverage can be provided only by space-borne instrumentation. In order to be successful, more *in situ* or near-ground ground-truthing for the remote sensors will be required.

Sampling Technologies

There has been and will continue to be a need for a wide variety of sample collections at diverse locations during all times of the year. Improvement and development of, new sample-retrieval technologies will be critical. All types of samples are needed, including ice, rock, sediment, water, air, and biological specimens, from bacteria to large animals, and flora as well as fauna. There is a need for "clean" sampling technologies that recover pristine samples, eliminating artefacts due to sample collection, handling, storage, and transport. In some instances, recovery and maintenance of samples at *in situ* conditions (temperature and pressure) may be desirable and/or required to ensure the integrity of the samples. Development of sample-retrieval technologies that can complement and be performed by observatory platforms will be needed to calibrate and ground-truth sensors and for the provision of samples for analyses of variables and properties that cannot be easily sensed. Because of the expense of sample collection it is highly desirable that international repositories and archives be expanded to facilitate and maximize wide use of samples, and to preserve samples for analyses that are not yet feasible or of those variables that may become of interest in the future. Sampling techniques developed in other regions of the world may need to be adapted to the requirements of use in the Polar Regions, but many can be directly applied, such as those routinely used in oceanographic studies and, in particular, those used in the deep sea elsewhere.

Data and Computational Requirements

Data accessibility and sharing is a universal topic of discussion in international science in general, and the requirements for Antarctic science are much the same as in other settings. Many of the anticipated advances in technology will result in "big data sets". Access to greater computational power and speed will be critical for future Antarctic research. Real-time data acquisition and availability are crucial for some disciplines. A continued emphasis on data sharing, distribution, and standards is fundamental to modern Earth System Science. Better and more-integrated platforms for high-performance computing to handle the rapidly growing "big data" requirements are needed and must be made more widely available. Such computing capabilities underpin modelling, experimental designs, automated image analysis, and bioinformatics. There are major challenges associated with producing and handling "big data sets", and adequate bandwidth and transfer rates (including transfer rates under water) are among these.

Earth System Models

An integrated system science approach is crucial to improving modelling and predictive capabilities across all disciplines and topics. Improved Earth System Models are needed for weather and climate modelling and data re-analyses; process-driven numerical modelling is essential for predicting the behaviour of ice sheets, and improved ecosystem models are needed to test hypotheses, design experiments, and inform conservation management. Holistic, interconnected models of all system components will be essential. Assimilation of "big data sets" and efforts to integrate observations and models will be critical to advancing understanding and prediction of feedbacks, thresholds, and "tipping-points". Modelling non-linear relationships and threshold responses remains a challenge to predictive capabilities. Historical records are essential for "back-casting" and model testing.

Unmanned aerial vehicle used for science support

Photo: KOPRI

Antarctic Remote Sensing Science

–T Wagner and C Webb, NASA Cryospheric Program, pers. comm.

"Remote sensing science of Antarctica and the Southern Ocean requires corresponding *in situ* measurements and research to maximize the scientific return from the satellite observations. The specific activities required are:

- Calibration and validation of satellite remote sensing data
- Logistical support for remote sensing by manned aircraft and UAVs
- *In situ* observations and research to be combined with remote sensing work to answer key science questions

Future work will require infrastructure that can support *in situ* and airborne activities over the complete range of environments on the Antarctic continent and in the Southern Ocean during all seasons. If this operational need is not met, it will not only degrade the utility of the remote sensing observations themselves, but also impinge on the most important science for connecting change in the Earth's southern Polar Regions with the global system."

SCIENCE-THEME TECHNOLOGIES

While there were broad technological needs identified that cross-cut scientific disciplines and themes, the details of the technological needs were often specific to particular research and science topics or clusters. Integration across disciplines and topics will be essential for the most cost-effective use of resources. This section presents those technologies for each specific cluster.

Antarctic Atmosphere and Global Connections

The highest-priority technological advances for Antarctic atmospheric sciences research are summarised in Box 1. These technological requirements were considered to be of equal importance to accomplishing the research necessary to answer the highest-priority Antarctic atmospheric science questions. Continuous measuring sensors and remote weather stations with expanded and robust sensor arrays were considered to be intrinsically linked, as Automated Weather Systems (AWS) provide the continuous measurements needed to answer many questions. Technologies for "smart" (unattended) deployment are critically needed. Meeting the power requirements for autonomous (robotic) systems will be a challenge. Improved battery technologies and the development of UAS will most likely occur in the private, commercial sector and the Antarctic community needs to keep abreast of these developments and work to adapt the latest technologies for application in the Antarctic. Enhanced linkages between atmospheric research and modelling and operational forecasting will be essential for improving regional and local weather forecasting and enabling efficient planning of field studies. Antarctic programmes with the best forecasting capabilities complete more field work. In regard to forecasting abilities, better coordination of operational meteorology activities amongst national programmes may be beneficial. The vital importance of improved sea-ice forecasting in support of logistics efforts was noted and there are lessons to be learned from experiences in the Arctic.

Improved models are needed to answer many of the highest-priority atmospheric sciences questions. This can best be accomplished by close coordination of observations and models. The advancement of models is closely tied to the availability of cyber-infrastructure, especially high-performance computing, and the availability of databases. Modelling efforts must expand the range of climate system components included in Earth System Models. More-advanced models are needed to support "system reanalysis" efforts as well to fine-tune models. Partnerships beyond the Antarctic community will be essential to advance models, including with the World Meteorological Organization's Experts on Polar and High Mountain Observations, Research and Services group and national space agencies, all of which are focused on improving observations, Earth System Models, and data availability. Advanced data analysis requires improved connectivity (higher-bandwidth connections) and power technology (a mixture of improved technologies for energy generation/storage and minimisation). Google Project Loon could be a potential supplement to satellite communications, and UAS have not been fully examined as a potential communications link in the Antarctic.

Remote sensing is a critical technology for answering many high-priority atmospheric science questions. The Antarctic community needs to more fully engage with national space agencies to ensure their needs are represented in planning efforts. The need for deep-ocean drilling to recover palaeoclimate records was noted and is discussed in other sections of this report.

Scientific advancement of Antarctic atmospheric sciences in the next two decades will be critically dependent on the improved exchange of people and information – including improved logistic coordination, technology transfer and dissemination, and availability and coordination of databases.

BOX 1

- Improved satellite remote sensing
- Data transfer in real-time and connectivity
- Improved Earth System Models
- Observing technology capable of being autonomously deployed and sustained (including being adequately powered)

BOX 2

- Underwater (and under floating ice) navigation and positioning
- Bandwidth and continuity of data communication from remote locations (specifically underwater)
- AUVs and gliders with greater range and capacity
- Long-term ice and deep-water capable buoy networks (including ice-tethered platforms/profilers, sea ice buoys, drifters and moorings)
- Unmanned biological and physical sensors/observatories (with consideration given to power needs/greater efficiency)

The Southern Ocean and Sea Ice in a Warming World

The highest-priority technological requirements needed to advance the research necessary to answer Southern Ocean science questions are summarised in Box 2. An overarching goal of ocean sciences research is much greater automation of measurements and lessening dependency on ice-breakers to perform field work. Several of the technological improvements necessary to move towards greater automation include the further development of AUVs, gliders, Remotely Operated Vehicles (ROVs), floats, and drifters. Improved underwater and under-ice navigation and positioning is needed to accurately emplace these platforms. Developments in this field are underway and prototype technology exists. However, these technologies must be made more widely available, and major improvements are needed.

Increased bandwidth and faster transfer of "big data sets" from Antarctica are critical limiting steps to future Antarctic oceanic research. Data transmission through the ocean is a particular challenge. Presently this is done by cable, sonically (limited bandwidth), and/or by the release of data capsules to the surface. Enabling real-time or near real-time transfer of data via satellites and/or high-altitude UAVs is one possible solution. Automation of measurements and observations can be fully utilised only if wider bandwidth is available for data transmission. Moving towards greater automation will also require more-stable and long-duration power supplies. The range of present AUVs and gliders is limited by power. The development of smaller and more-powerful batteries combined with smaller and less expensive sensors that consume less power will be critical to the development of the next generation of long-range autonomous ocean sensing platforms. Expanded, environmentally and ethically conscious use of animals as platforms for sensors is needed.

Greater automation and less dependence on ice-breakers can be accomplished by developing long-term networks of buoys, moorings, ice-tethered platforms (including ice buoys), and drifters. Current moorings can be deployed for about two years. In the future, at least five-year deployments will be needed. This will require long-lasting power supplies and stable sensors. Present drifter networks need to be adapted for use in under-ice environments (coupled with improved navigation/position capabilities), the deep sea, and in

Antarctic Ice Core Science

– International Priorities and Challenges in Antarctic Ice Core Science: A Contribution to the COMNAP Antarctic Roadmap Challenges, International Partnerships in Ice Core Sciences (IPICS). **Co-Chairs E Brook and E Wolff**

The five priority projects are:

- The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica.
- History and dynamics of the last interglacial period from ice cores.
- The IPICS 40,000 year network: a bipolar record of climate forcing and response.
- The IPICS 2k Array: A network of ice core climate and climate forcing records for the last two millennia.
- Solving ice core drilling technical challenges to advance the science.

"Although requirements … can be met with currently available technology, some will require the extension of current technologies or the development and testing of new ones. Technical requirements … fall naturally into two sets – those related to deep-drilling projects and those related to the shallower projects."

"The ice deep drilling for oldest ice will require improvements in drilling fluids, applying successful strategies for recovering good quality cores through the brittle ice zone, institutionalizing successful approaches to core recovery in warm ice and developing methodologies for obtaining replicate samples."

Shallower ice projects "require the identification and standardization of a lightweight … capable, wet drilling system with simple logistical requirements and short setup and breakdown requirements."

shallow-water environments. Ice-tethered platforms (including ice mass-balance buoys) capable of longer duration emplacements are needed. Also needed are interoperable unmanned observatory hubs that support a wide range of observations (weather stations, ice radar, ocean measurements cabled up from moorings, gliders/AUVs or buoy networks), providing power, data-collection capabilities, and the ability to transmit data from the field via satellite and/or air links. Cabled observatories elsewhere in the world's oceans are under development, testing technologies that might be applied in the Southern Ocean.

Satellite-based sensors are important for ocean research as they provide long-term, year-round observations. Ground-truth of data from satellite- and air-borne sensors will remain a high priority, requiring sustained and year-round access to the region. Presently, the only ways to obtain winter-time data of the surface waters of Antarctica are through satellites and instrumented mammals. Animal-based technologies need to be made more widely available and less expensive sensors need to be developed. Scientific questions about palaeoclimate and extreme events require the retrieval and study of deep-sea and coastal and interior basin sediment records. Core drilling/recovery and sediment retrieval are existing technologies that are not readily available to Antarctic scientists due to the high cost of operation in the Antarctic region.

The Ice Sheet and Sea Level

The highest-priority technological advances that will be needed for accomplishing the research to answer ice-sheet and sea-level scientific questions are summarised in Box 3. Improved predictions of change and response to forcings are essential. The integration of models with a wide range of in-field observations will be critical to developing the next-generation ice-sheet models capable of describing and predicting realistic ice flow. These improved models need to be an integral element of holistic Earth System Models. Model improvements are mostly hindered by a lack of knowledge/observation relating to key processes, which emphasises the need for integration of modelling and field data. A better understanding of the influence of bed topography, ice fabric, basal heat flux, underlying sediments, temperature, and other basic parameters is important for improving models. Comprehensive and more-accurate ice-sheet mass-balance measurements are also essential. Knowing the flow of ice in vertical profile in all places, from the interior to the grounding zone, is needed to adequately describe the factors that influence ice-sheet dynamics. Ice-sheet models have improved considerably but substantial improvements are needed to better constrain predictions and to describe the "real" flow of ice in Antarctica.

BOX 3

- Process-driven numerical ice sheet modelling
- Subglacial sampling methods, including for sediment recovery
- Combined multiple geophysical measurement and sampling of ice, including by UAVs
- Satellites making synoptic, operational measurements of snow and ice accumulation
- AUVs and submersible sensors

While improvements in ice-sheet modelling are essential, there are several other priority needs. Knowledge of ice- and snow-accumulation rates is poor, and improvements will require satellite observations. Ice-sheet flow is affected by basal processes and ice rheology, both of which are not well described in models. To obtain the necessary observations, sampling of the subglacial environment and en-glacial environments is needed. To guide sampling efforts, more-detailed geophysical imaging and mapping of the ice sheet is needed. Critical regions of the ice sheet, such as grounding zones and shear margins are challenging for deployment of personnel and equipment. Technological solutions include the use of remotely deployed expendable instruments. Also critical to ice-sheet change are ice-shelf and grounding-zone processes, requiring both on-ice and sub-ice-shelf measurements. Coordination of these studies with oceanographic observations is critically important. Potential exists to use UAS to expand geophysical data coverage. Application of existing private sector 3-D seismic techniques would provide transformative insights into basal processes and ice structures. Miniaturisation of equipment and sensors will be important for Antarctic applications. Miniaturisation brings important savings on weight and power, extending deployment times. The anticipated "big data" from instruments will require sub-orbital communications networks to optimise utilisation of next-generation of ice-sheet measurements.

The Dynamic Earth Beneath Antarctic Ice

The technologies necessary to address high-priority scientific questions in the geosciences are summarised in Box 4. Many of the requisite technologies exist, are under development, or require improvements that are achievable in the short term. Key for the advancement of geosciences is improved availability of existing technologies that allow for regular/repeated collection of a wide range of samples and data at a variety of sites. Other technologies, such as subglacial bedrock/sediment-core recovery and satellite-hosted payloads will require a number of years to develop. Ensuring the standardisation of sensor technology and the connectivity and interoperability of sensors is a high priority. It will be essential that multi-sensor networks and platforms be adopted by the international community to facilitate collaborations and cross-disciplinary science. Multi-sensor, multi-tasking observatories and platform networks that support integrated experiments will create efficiencies in resource utilisation.

The highest-priority geosciences questions can be fully addressed only by access to large spatial areas on the continent and the surrounding oceans. To answer some questions, broad access to East and West Antarctica is needed so that sensor arrays capable of acquiring continuous year-round data can be deployed. Sensor networks will need to be capable of acquiring and transmitting high volumes of data, will require increases in bandwidth, improvement in power sources suitable for the Antarctic environment, low-power-consumption instruments, and efficient energy management.

The technological requirements for sensor networks, ice borehole drilling, sampling of subglacial sediment, and rock and sensor emplacement will also support many of the requirements in "The Ice Sheet and Sea Level" cluster (geophysical equipment, AUVs, ROVs, geophysical wave gliders, and subglacial and ocean drilling). Palaeoclimate records of greenhouse conditions, both sub-ice and from oceanic rock and sediment, are needed for answering questions in the "Antarctic Atmosphere and Global Connections" cluster. In addition, geophysical data, sensors, and samples will allow for a better understanding of the distribution and volumes of greenhouse gases stored in permafrost and clathrates. Samples of sediment and rock also provide information about ecosystem evolution over Earth's history.

Technology development is an important component of subglacial research. Clean, rapid, reliable access through thick ice to the subglacial environment is a requisite. Obtaining samples cleanly, and returning them to the ice surface without contamination is essential for this work. It is important that a temporal record of measurements be obtained from *in situ* observatories for a true understanding of contemporary ecosystem dynamics and how these processes will respond to global changes.

BOX 4

- Sensor arrays on the continent and in ice/subglacial boreholes
- Technologies for collection of data and samples during field surveys (UAS, field sampling, miniaturisation, low power requirements, robotics, etc.)
- Drilling systems for the collection and complete recovery of samples of sediment and rock from beneath the ice and the ocean

Life on the Precipice

This cluster of questions covers the marine and terrestrial (including subglacial) environments, and spans as wide a range of organisms, from bacteria to marine mammals, encompassing a wide variety of themes in biology and ecology. Given this diversity, the key technologies required (Box 5) are sensors for both structural (species detection) and functional (e.g. nutrients, CO_2) purposes, to be used in environments from the subglacial to the marine. These sensors would range from those on satellites to those in UAVs. Much of the work required to address the life sciences questions will require automated sampling and robotics. The "omic" approaches (e.g. genomic, transcriptomic, meta-bolomic) are a key part of this work. *In situ* -omic platforms that allow real-time analysis and onward transmission of data (rather than samples) will require deployment across a range of geographical sites.

Modelling, bioinformatics, eco-informatics and associated approaches will require increasing access to high-performance computing. Accessibility of such computing, both in the Antarctic and at home institutions, is essential. High-speed communication via satellite, microwave, and other technologies will be a significant requirement to deliver future life sciences research. Such communication includes capabilities from ships, given their ongoing significance for deep-sea work, and data collection by AUVs, UAVs, buoy networks, and gliders. Antarctic researchers must be aware of technologies developed elsewhere in the world, and must be proactive in applying the latest and most sophisticated technologies to life sciences research in terrestrial and marine environments.

While oceanographic conditions may need to be measured during life sciences studies, the spatial and temporal variability of biota and biotic processes often necessitates more-demanding sampling

Antarctic Subglacial Lake Exploration

***–White Paper – Antarctic subglacial lake exploration*, M Siegert, J Priscu, I Alekhina, J Wadham and B Lyons (Conveners): 7th International Meeting on Antarctic Subglacial Lakes, Chicheley Hall, 30–31 March 2015.**

"It has been 20 years since Subglacial Lake Vostok was hypothesised to harbour a unique microbial community that evolved in isolation over millions of years, and contained ancient records of past climate. Subsequent research made it clear that testing these hypotheses is possible only through direct measurement and sampling of the lake water and sediment."

Three priorities for future research were identified:

- technology for clean, reliable deep-ice access and subsequent *in situ* data acquisition is a pre-requisite for subglacial lake exploration
- a variety of subglacial environments should be considered for exploration for the full extent subglacial biodiversity, and cross-correlation of climate records, to be evaluated; and
- international cooperation is desired for scientific optimisation, allowing the sharing of logistics, equipment and samples.

"Targets for future exploration include deep-water lakes at the ice-sheet centre, hydrologically 'active' lakes closer to the continental margin, and other environments including former subglacial lakes now covered with thin ice and deep sedimentary basins where extensive groundwater may exist."

Within the category of extraordinary logistics requirements, "missions to Lakes Whillans and Ellsworth demonstrate that sophisticated equipment and substantial loads can be transported via over-snow traverses from the ice sheet margin, where logistic hubs exist – to the ice sheet interior. For the case of Lake Vostok, the use of a major permanent interior ice station made the research possible. … [S]easonal camps supported by ski equipped aircraft … will be required to access and sample the majority of subglacial lakes."

BOX 5

- Improved sensors, more-robust sensors with automated calibration, sensor networks, and higher sensor resolution for monitoring *in situ* structure and functional processes and compounds
- Robotic (controlled and autonomous) multi-purpose systems and vehicles for continuous and long-term *in situ* process monitoring and multi-sample recovery and return
- Better and more-integrated platforms for high performance computing for rapidly growing "big data" requirements
- High-volume automated multi-omic platforms for phylogenetic and functional analysis of multiple large-scale meta-omic sample sets, including automated *in situ* meta-genomic analysis and integrated bioinformatics analysis
- High-volume satellite/microwave bandwidth for integrating Antarctic data capture and both on-site and off-site analysis

BOX 6

- High-bandwidth networks on- and off-continent, and continual data transfers in real-time from locations throughout the Antarctic
- Energy-efficient high-performance computing hardware and advanced data analysis techniques
- Remote/robotic observatories optimally and strategically deployed across the plateau

Polar Solar Terrestrial Science

– M Lessard, A Gerrard, and A Weatherwax (eds.): *Solar-Terrestrial Research in the Polar Regions: Past, Present, and Future* (University of New Hampshire, 2014)

"Antarctica provides a fundamentally important observing platform critical for understanding the effects of the Sun on Planet Earth, and the potentially deleterious effects that have important societal and technological implications related to space weather. … [T]he Antarctic continent provides a large land mass that supports observations at the highest geomagnetic latitudes, where energy from the solar wind easily penetrates Earth's magnetic field at the polar cap. … [B]ecause of the approximately 23 degree tilt between the Earth's spin axis and its magnetic field axis, the so-called 'auroral zone' remains in complete darkness throughout the 24-hour day during the austral winter. This offset enables significant dayside observations of aurora to be acquired only in the Antarctic. Of further importance are inter-hemispheric differences in solar wind coupling to the geospace environment. … [T]he Antarctic enables studies that use Long Duration Balloons (LDB) that reveal information about Earth's radiation belts and energetic particle precipitation that drives aurora and atmospheric processes. … LDB missions are more readily accomplished in the Antarctic due to … the spirit of scientific collaboration fostered by the Antarctic Treaty. …

"Recent advances in critical engineering and logistic support will facilitate … and enable the deployment of new instrumentation across the Antarctic [, improving our] understanding of geospace … [and] ushering in a new scientific age of polar exploration."


Photo: KOPRI

Jang Bogo Station with aurora

regimes. A key requirement will be to put platforms (observatories/sensors, ships, etc.) in the scientifically interesting places at critical times. One approach is to have rapid response teams that can respond to unforeseen seasonal events that have profound impacts on the trajectories of marine ecosystems. Life sciences research has a major role to play in Antarctic conservation efforts, particularly in the marine realm in support of establishment of protected areas, setting of fishing quotas, ecosystem-based management schemes, and predicting the response of ecosystems to past and future resource extraction within the context of a changing and warming climate. Critical to life sciences research is improved ecosystems models linked to Earth System Models that connect environmental drivers and ecosystem structure and function.

Near-Earth Space and Beyond – Eyes on the Sky

The highest-priority technological challenges faced in using Antarctica as a platform to gaze into space are summarised in Box 6. Next-generation large single-dish telescopes will require novel telescope designs (e.g. segmented mirrors) in order to be transportable to remote Antarctic locations. Technologies to facilitate this might include off-axis mirrors, lightweight (carbon fibre) mirrors, and high-precision inertial pointing systems. There are significant trade-offs between communications bandwidth and capability for on-site data processing. The former is dependent on the infrastructure provided by the national programmes; the latter requires significant advances in energy-efficient high-performance computing hardware and/or the availability of more electrical power. Full answers to the questions related to the Dark Universe and extra-terrestrial life will require the deployment of optical/infrared telescopes to the interior of Antarctica. Engineering risks for large telescopes will need to be addressed through a series of pathfinder experiments.

Research in the Polar Regions also supports the high-latitude observations needed to understand fundamental aspects of coupling between the solar wind and Earth's atmosphere, ionosphere, and magnetosphere. The vast geographical regions in both hemispheres provide access to a broad range of geophysical phenomena, spanning magnetic and geographic latitudes from the sub-auroral zone to the polar caps, at altitudes from the troposphere to near-Earth space. While the northern hemisphere is relatively well instrumented with regards to near-Earth space observations, the southern Polar Region is not, primarily because of the extreme Antarctic climate and the lack of manned facilities with infrastructure. The situation in the southern hemisphere, however, is changing with the development of technologies that support autonomous measurement systems that can be deployed in remote locations and that operate unattended for long periods in severe environments.

Human Presence in Antarctica

Research regarding the human dimensions of Antarctica encompasses a diverse set of questions that integrate the life sciences and a range of social sciences and humanities disciplines, including anthropology, economics, history, human geography, law, political sciences, and social psychology. The integration of methods of inquiry from such a wide range of disciplines requires the availability of suitable technologies and a reduction of barriers that go beyond technological requirements, such as access to materials, actors, and information (Box 7).

BOX 7

- Advanced data analysis techniques utilising high-performance computing and improved bandwidth
- Improved ecosystem models
- New and better sampling and handling technologies
- Better sensing and surveillance technologies and tracking systems, including autonomous tracking devices (e.g. for vessels, for landings, for land vehicles, and for scientific expeditions and other land-based human activities, such as camp sites) and smart technologies
- Imaging and recording equipment suitable for use in extreme climate conditions

The technologies required to address the Human Presence questions are similar to those for Life on the Precipice. High-performance computing for advanced modelling both in the life and social sciences is a key requirement. Better sensors, and broader deployment, both in space and time, of such sensors, including robotic and automated sampling, will be required to understand impacts. For example, understanding new contaminants and the arrival of new species, and the impacts of both, requires such sampling. In marine systems, automated systems for understanding fishing impacts will be essential, coupled with information on the scope and extent of such resource extraction. Sensing, surveillance, and tracking systems to provide information on movements of vehicles of all kinds and to understand visitor access to various sites will require deployment and, in some cases, development. At the same time, it is worth noting that attention should also be paid to technologies that assist in mapping and assessing existing material legacies (e.g. building remains or artefacts) in the Antarctic in a coherent and systematic manner.

While high-performance computing and improved sensing and robotics technologies are essential to address the environmental science aspects of questions in the Human Presence cluster, there is also a pressing need to overcome barriers to data access. To effectively address the questions related to human impacts and governance, detailed information about human activities in the Antarctic that is recorded by the operators or facilitators of the activities – from science operations to tourism to fishing and other commercial activities – needs to be more accessible.

For many of the humanities- and social science-focused questions, the key technological constraints are small. However, access to the continent for social scientists and humanities researchers, as well as access to information and improvement of this access, is significant. An element of this opportunity to access goes to the need to improve understanding of the use of privileged information. The humanities and social sciences have well-developed codes of practice for the use of such information. Importantly, little progress will be made on several of the key questions without better general appreciation of the need for the collection and provision of such data.

THE STATUS OF TECHNOLOGICAL REQUIREMENTS

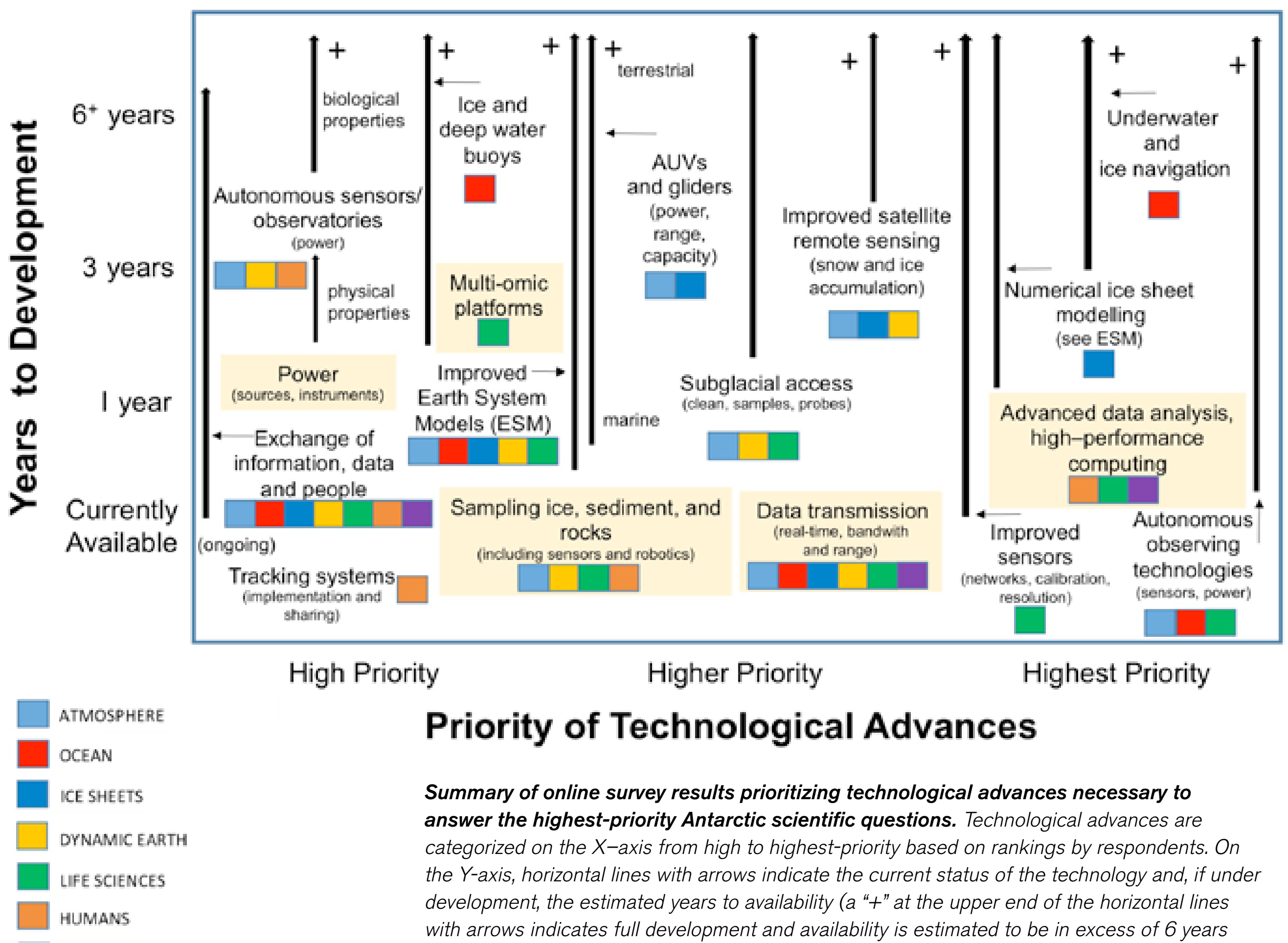
Once identified, technological advances were assessed as to current status and whether the technologies were available or under development and when they would be accessible: in the short-term (1 to 3 years), the medium-term (3 to 6 years), or the long-term (6 to 9+ years) (Figure 1). In some instances technologies are available but need various refinements, improvements, or adaptations to the specialised circumstances/conditions in the Antarctic. An analysis of the outcomes of the considerations of the status of high-priority technologies suggests there are several factors at work that control wide usage: availability, needed improvements, application of technologies available elsewhere to Antarctic science, and development of new technologies. Each of these considerations requires differing actions to ensure that the greatest scientific return is realised.

A number of technologies were identified as currently available but available only to a relatively select set of scientists. To improve access to existing technologies, partnerships, coordination, and sharing of facilities are needed. Other technologies are currently available in one form or another but would be improved by refinements (i.e. data transmission in terms of bandwidth and real-time capabilities, sampling equipment and techniques, and autonomous/robotic vehicles of various types). In other instances new technologies are required, such as power systems to improve the range and duration of deployments, advanced computing, and new sensors. Advancements in a number of technological areas will most likely come from outside of the Antarctic science community and the challenge is applying them to the southern Polar Regions – e.g. multi-omics platforms, computing capabilities, and autonomous vehicles and robotics. It is also apparent that many of the technologies are under continual improvement and that advances will incrementally occur over a number of years. The rate at which technological challenges will be addressed is fundamentally controlled by the magnitude and rate of sustained investment and the ability of the community to coordinate and focus efforts on high-priority needs.

Improved models and predictive capabilities are ongoing needs, and various types of models are at differing stages of sophistication and maturity. Challenges facing modelling include coupling models of various kinds and assimilation and availability of data. It was also evident in the survey that a wide range of technological advances would benefit a wide swath of the Antarctic science community. As can be seen in Figure 1, common needs were identified across disciplines and scientific topics. This suggests that broad support and concerted community-wide efforts will be most effective in further defining and addressing those technological challenges seen as limiting by a diverse group of potential scientific end-users. Therefore, integrated technologies and platforms that serve multiple purposes and support varied applications are essential in order to optimise investments. Integrated technologies also represent opportunities for partnerships and coordination amongst nations and scientists.

In summary, the highest-priority technological advances needed were improved autonomous/robotic observing systems and the available and supported sensors (including power supplies), advanced data analysis and computational needs (communications and information technologies), improved satellite remote sensing (sensors, coverage, and availability), and improved coupled models of all kinds. These analyses allow those that invest in technologies to assess where contributions might be made over varying timeframes, providing an indication of the most efficient use of funds for greatest scientific return and where partnerships might be beneficial.

Figure 1. Summary of the estimated years to development/availability of those technological advances identified as highest priority



Priority of Technological Advances

Summary of online survey results prioritizing technological advances necessary to answer the highest-priority Antarctic scientific questions. *Technological advances are categorized on the X–axis from high to highest-priority based on rankings by respondents. On the Y-axis, horizontal lines with arrows indicate the current status of the technology and, if under development, the estimated years to availability (a "+" at the upper end of the horizontal lines with arrows indicates full development and availability is estimated to be in excess of 6 years from 2015). Coloured bar codes indicate which science clusters ranked the indicated technology as a priority need (see the colour key at left). Note that coloured bar codes indicate highest priorities within scientific question clusters but the absence of a cluster does not indicate that the technology is not applicable – i.e., it did not rise to being highest priority for the cluster's specific scientific questions. Technologies in beige boxes include a wide range of associated or supporting technologies and therefore a time frame for development is not indicated as it is highly variable.*

Concordia traverse 2013

Photo: PNRA

ACCESS, INFRASTRUCTURE, AND EXTRAORDINARY LOGISTICS REQUIREMENTS

Based on the technologies currently used and those identified as expected to be used in the future, the focus of discussion then became the requirements for access, infrastructure, and logistics.

The majority of Antarctic research is field-based and will continue to be for the foreseeable future, and access can often be a critical limiting factor in conducting research to answer a wide range of high-priority scientific questions. The preponderance of observations and measurements, other than by satellite-based sensors and autonomous observatories, have been made during the austral summer, due to the difficult operating environment during other times of the year. Many scientific questions will require continent- and ocean-wide access year-round. Results from the ARC indicate that across all clusters, access – to coastal areas (including beneath ice of all kinds – floating and grounded), the interior of Antarctica (including deep field camps), and the Southern Ocean – was seen as highest priority (Table 2 and Figure 2). A need for the establishment of “super sites” of high scientific interest to concentrate interdisciplinary, cross-cutting science was identified. A bipolar network for continuous atmospheric monitoring was seen as high priority for logistical as well as scientific reasons. In regard to infrastructure and logistics, increased ship time (including with ice-breakers) and on-site laboratories were seen as high priorities, but it was unclear that current Antarctic infrastructure was limiting. More-effective utilisation of existing or planned facilities amongst nations, rather than expansion of infrastructure, was seen as a way to increase scientific return. The high initial and ongoing maintenance costs of permanent infrastructure were seen as potentially limiting important investments in other areas.

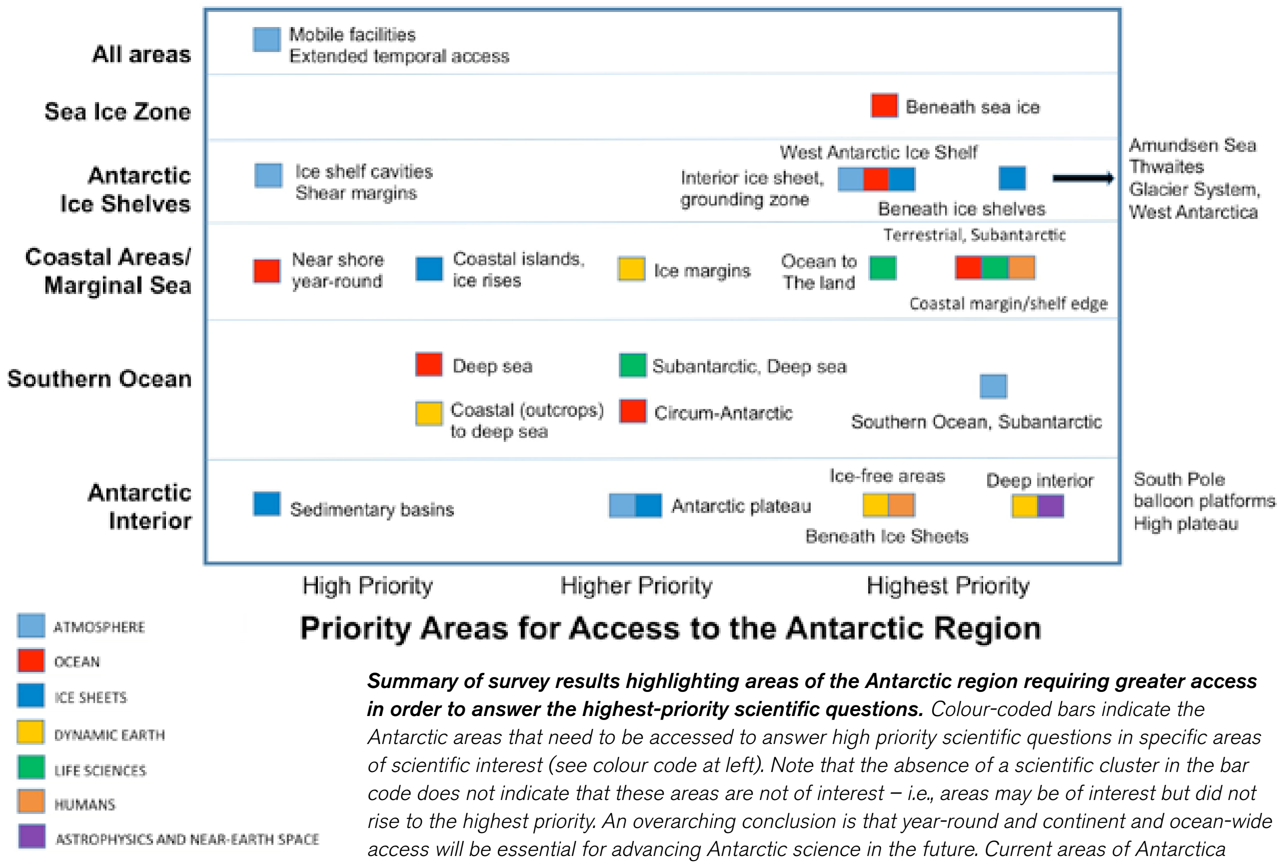
Access beneath floating ice (sea ice and ice shelves) is emerging as a common goal to address a wide range of scientific questions. Access to remote areas will require greater international collaboration and more-effective utilisation of existing stations. Improved access to research-capable ice-breakers – through greater continuity in availability, coordination, and year-round scheduling – is desirable. Cost considerations mean that the development of additional ice-breaker capacity must be balanced against other needs for wider geographic and year-round access. For Southern Ocean research, access needs stretch from the deep ocean, across the continental shelf, to near-shore environments (including ice shelf cavities).

The List (as it appeared in the survey: alphabetically)	**Number of times chosen**	**Overall ranking (1=most important)**
Access to coastal regions	86	1.69
Access to the deep ocean for sampling and emplacement of observatories	25	2.36
Access to the interior of Antarctica	70	2.13
Airborne sensors	27	2.93
An inter-hemispheric near-Earth space monitoring network	7	3.29
Benthic and pelagic oceanic sampling gear	29	2.48
Deep field camps	39	2.87
Deep-sea manned and unmanned submersibles	18	2.89
Deep-sea towed video and sensor arrays	5	2.80
Deployment of ultra-long duration balloons	8	2.63
Expanded telescope and astrophysics sensor arrays	8	2.88
High-plateau research station	23	2.65
Increased ice-breaker availability	51	2.71
Increased ship availability	48	2.48
Networks of buoys in the ocean	18	2.89
Network of stations continuously conducting atmospheric monitoring in both Polar Regions	35	2.80
Network of stations continuously conducting wave energy monitoring	8	2.75
Network of stations continuously conducting under-ice monitoring	15	3.27
On-site laboratories for sample processing	46	3.09
Open-access databases	55	2.98
Remote placement of instrument arrays	30	2.80
Shelf- to deep-sea monitoring stations	15	3.56
“Super-sites” where suites of observing tools (ocean, surface, air) create a common “natural laboratory”	31	3.55
Trans-continental access	7	3.14
Traverse capabilities	26	3.00
Under-ice sheet monitoring and observing	17	3.47
Under-ice shelf monitoring and observing	25	3.04
Under-sea ice monitoring and observing	25	3.08
“Wet” storage (long-term storage of genomic materials under cool temperatures)	19	3.47
Year-round access to the continent	30	3.47
Year-round access to the Southern Ocean	34	3.32

Other (Access-related) [free text]: Geographic information, Antarctic stations & personnel, Year-round sea ice, Data networks, Easier permitting, Historical sites, Remote sensing, Open meetings, Operations information sharing, Remote rock outcrops, Humanities support, Tourist sites. Other (Infrastructure-related) [free text]: Communication networks, Animal-borne sensors, CTDO instrumentation for water collection, Surface snow observations, Telemedicine capabilities, Increased ship-based helicopters, Fishing, Aquaria, Multibeam, integrated cryosphere observing sites, Ocean gliders & floats, Sub-ice geological drilling, Intercontinental biological sample transport.

Table 2. List of access, infrastructure and logistics requirements as presented in ARC survey 2

Figure 2: Summary of the access requirements identified as highest priority



Summary of survey results highlighting areas of the Antarctic region requiring greater access in order to answer the highest-priority scientific questions. *Colour-coded bars indicate the Antarctic areas that need to be accessed to answer high priority scientific questions in specific areas of scientific interest (see colour code at left). Note that the absence of a scientific cluster in the bar code does not indicate that these areas are not of interest – i.e., areas may be of interest but did not rise to the highest priority. An overarching conclusion is that year-round and continent and ocean-wide access will be essential for advancing Antarctic science in the future. Current areas of Antarctica experiencing accelerating environmental change are of high interest and areas of high scientific interest will evolve as scientific questions advance.*

In the future, the optimal locations for science measurements/experiments/observations may be remote from permanent stations. Solutions to the need for greater geographical access without additional permanent stations include greater automation of deployable observatories and platforms, the development of modular and relocatable laboratories/facilities, temporary stations, and greater utilisation of existing facilities to support expeditionary-style field programmes. An ability to rapidly deploy teams of scientists to rapidly changing regions to collect benchmark observations was seen as a priority as well. Communications and Information Technology (C&IT) is an indispensable and growing demand on Antarctic infrastructure. Supply-chain logistics, personnel deployment, the management of scientific research support (e.g. for astrophysics and geospace sciences), handling and transfer of automatic remote observations (e.g. Automatic Weather Stations, POLENET), and telemedicine capabilities are critically dependent on adequate and reliable C&IT (Blue Ribbon Panel, 2012).

Antarctic Atmosphere and Global Connections

Many atmospheric science questions are linked to teleconnections at the hemispheric scale and can be addressed only through broader sampling across the region, including all areas of the Southern Ocean, the West Antarctic Ice Sheet, difficult-to-access interior parts of East Antarctica, and the sea-ice zone. Opportunistic access to all areas should be capitalised on to make a wide range of atmospheric observations and measurements. Data collected from the sea-ice zone is particularly important for understanding interactions between the cryosphere and atmosphere, ozone chemistry, and air–sea flux changes. To access these areas to conduct atmospheric sciences research, the following infrastructure and logistics are high priority:

- Dedicated ship-time that provides year-round access to the Southern Ocean, the sea-ice zone, and the continental coast. Understanding underlying atmospheric and ocean processes, especially at critical interfaces (ocean–atmosphere–ice–land) will require multidisciplinary cruises and expeditions to collect synoptic measurements.
- Integrated traverse and aviation capabilities that allow repeated access to the interior of Antarctica to emplace and service observatories.
- Temporary or permanent land stations or expeditions into the West Antarctic Ice Sheet region, as the region will continue to be an important focus for research of various kinds. Multi-national expeditions might be one solution.
- Drilling capabilities for the recovery of terrestrial and marine sediment climate records. Ice core drilling and recovery are equally important and are well-developed activities for which extensive plans for future use are in place.
- Opportunistic collection of atmospheric data by placing instrumentation on vessels and aircraft that are conducting other studies and/or transiting the region. Such instrumenting would expand the network of instruments collecting atmospheric CO_2 concentrations and other data.

Sharing and coordination of data collection are critical to ensuring greatest scientific return on investments. Cooperation and data integration would be facilitated by data quality assurance, inter-calibrations, standard methodologies, and sharing of technological advances. Coordination of real-time operational weather forecasting will improve the efficiency of resource utilisation and will minimise expensive delays and down-time.

The Southern Ocean and Sea Ice in a Warming World

Current areas of high interest for ocean research include the Ross Sea sector, West Antarctica, Prydz Bay, the Amundsen Sea, the Weddell Sea sector, and sub-Antarctic islands. Marine environmental-management information needs may require the study of other areas of interest. The highest-priority access requirements for ocean research are: winter/year-round access to the continental margin/shelf edge, including polynya; access beneath floating ice (sea ice and ice shelves); circum-Antarctic coverage; access to the deep sea; and year-round access to near-shore coastal areas. The most significant access challenge for ocean research is year-round access and, in particular, winter access. Winter access will require research-capable ice-breakers. However, due to the cost, investments in ice-breakers need to be balanced against alternative approaches that provide greater temporal and spatial coverage for oceanic observations and sampling efforts. Circum-Antarctic coverage is essential to developing a comprehensive understanding of ocean processes, oceanic interactions with ice sheets/shelves, and marine geology. Areas of current high interest include large embayments with floating ice, where interconnections occur and interactions play-out between the ocean and ice shelves/sheets.

AUVs and gliders are a partial answer, and these platforms must be capable of supporting a range of scientific measurements, rather than being highly specialised single-mission platforms.

To develop greater understanding of oceanic processes and links to global and biological systems there is a critical need for increased access to the deep sea and to near-shore, coastal Antarctica. Access to environments and regions beyond the reach of current Antarctic stations can be provided by remote observation technologies, unmanned observatories, and mobile research facilities. To access these areas the following infrastructure and logistics were deemed highest priority in support of Southern Ocean research:

- Improved access to research-capable ice-breakers – through greater continuity in availability, coordination, and year-round scheduling.
- Placement of ocean- and sea-ice observatories in high-priority areas (e.g. sub-Antarctic islands, the Amundsen Sea, the western sector of the Weddell Sea, the Bellingshausen Sea, and the eastern Ross Sea).
- Data infrastructure (data-sharing and data-management systems).
- Underwater docking ports to support AUVs, UAVs, gliders, and moorings. An overarching goal of ocean researchers is much greater automation. To extend the range and utilisation of AUVs, UAVs, gliders, and moorings the idea of interoperable underwater docking ports should be explored. Such docking stations must be capable of data collection and transmission and the provision of power to sensors and observatories.
- Improved coordination and collection of bathymetric data, including directed campaigns, is needed to fill major gaps in understanding the bathymetry of the ocean around Antarctica.

Some of the infrastructure and logistics challenges for ocean research are currently being addressed by international collaboration. However, there will be an ever-increasing imperative to expand collaborations and integration across national programmes and projects. The Southern Ocean Observing System (SOOS) is seen as a workable model that provides a framework for such cooperation and coordination. As above, data integration and sharing will be facilitated by data quality assurance, inter-calibrations, standard methodologies, and sharing of technological advances.

The Ice Sheet and Sea Level

In the last decade, rapid advances in observation and modelling have created high-priority geographic regional and glaciological targets for ice-sheet and sea-level research. Important regions to be studied are those that are particularly vulnerable to change. The highest-priority regions are either currently contributing significantly to sea level rise or are likely do so in the next century. Glaciological models and theories identify marine ice sheets (those parts of the ice that are grounded below sea level) and the associated grounding zones as most vulnerable to rapid and irreversible change. Current areas of high interest for ice-sheet and sea-level researchers are:

- The Amundsen Sea Embayment, Thwaites Glacier System, and West Antarctica.
- Marine margin to the interior of ice sheets, including grounding zones.
- The deep interior/Antarctic Plateau.
- Coastal islands and ice rises that contain palaeoclimate records of coastal regions and deep time in their interiors.
- Sedimentary basins that contain sedimentary records.
- Ice shelf cavities and systems.
- Shear margins where records of ice-sheet change are likely to be recovered.

Thwaites Glacier and its surrounding grounded ice and glaciers, ice shelves, and the Amundsen Sea are currently undergoing rapid change and are high priorities for study. There are numerous other marine ice-sheet basins in East and West Antarctica. Access to the Wilkes, Totten, Amery, Getz and other basins is also a high priority. These marine ice sheets are linked to the internal reservoir of the full Antarctic ice sheet and understanding their contribution to sea level will require access to the interior. The distribution of subglacial sedimentary basins influences the flow and stability of the ice sheet. Therefore, these basins are high-priority targets for access. Sedimentary basins may contain records of past climate changes that will improve our understanding of the response of the ice to climate forcings and provide valuable retrospective testing of model reliability. The stability and configuration of ice shelves that fringe marine ice sheets are important controls on the potential contribution of grounded ice to sea level change.

Understanding ice shelves and the adjacent grounding lines requires access to a complex and dynamic region of sea ice and icebergs on the one hand and crevasses on the other. Access to this part of the system is critical and will require technological innovation and significant logistic effort. In a similar manner, lateral shear margins of glaciers (which separate rapidly flowing ice from slow-flowing ice) are poorly understood features of the ice sheet that need study. These areas are difficult to access because of crevasses, but technologies similar to those proposed for grounding zones and ice shelves are applicable.

To access high-priority localities for ice-sheet and sea-level research, the following infrastructure and logistics were deemed high priority:

- A lengthened operation window for field work. Doubling the length of season could double the science conducted.
- Technologies may need to be deployed to multiple sites or established as long-term monitoring stations. Samplings efforts are needed over wide geographic areas over a period of many years to provide the density of data required to improve ice-sheet behaviour projections.
- Mobile and temporary stations. Much of the work needed to support ice-sheet modelling will continue to be remote from permanent stations. These efforts will need to deploy mobile, remote field parties and camps and be capable of supporting remotely operated sensors and rovers. The development of inland/plateau traverse capabilities based on electrical tractors and sledges is needed. These facilities need to be flexible and rapidly deployable.
- Fuel efficiency is of great importance. More-efficient deployment of fuel, as well as alternative/renewable energy sources, needs to be explored. Innovations are needed in solar panels and power systems for powering of large stations.
- Communications via a sub-orbital network may be needed to complement satellites.

Photo: J. Negrete, IAA

Weddell seal in the western Antarctic peninsula

- Improved and more-readily-available satellite and airborne remote sensing capabilities remain a continuing need.

The Dynamic Earth Beneath Antarctic Ice

Many high-priority geosciences questions will require studies on a continental scale. Large areas of the Antarctic will need to be investigated, and there is a need to access broad regions of East and West Antarctica.

- Access to the deep interior of the continent, especially in East Antarctica, is a high priority for studying supercontinent evolution; access to West Antarctica is a priority for studying volcanism and its impact on the ice sheet. There is critical need to visit interior sites to study rock exposures, deploy sensor networks, conduct airborne and other field surveys, and explore subglacial environments. Remote sensor networks need to be deployed; sediment and bedrock beneath the ice sheet need to be sampled. Airborne and geophysical surveys need to be conducted
- Access beneath the ice sheet is a high priority to advance understanding of Antarctic geology. For example, describing the subglacial geology of East Antarctic interior is essential to understanding supercontinent evolution, and interior subglacial basins may contain unique climate records. Observatories need to be deployed in a subglacial environment.
- Access to coastal Antarctica, including at ice margins, is needed for collection of outcrop samples. For example, the West Antarctic coast, particularly around the Amundsen Embayment and Marie Byrd Land, are mostly unknown. Access is limited by ship availability.
- Access to the Southern Ocean, from the coastal to deep sea, is required to collect sediment and rock records of climate history, to study ice–ocean interactions, and to decipher the tectonic evolution of Antarctica/Gondwana. For example, the Amundsen Sea Embayment, Wilkes Land, Ross Sea, and Scotia Arc are key areas of study for the marine geology community.

Many science objectives for Dynamic Earth require continental-scale observations. Synoptic observations from sensor networks and integrated drilling/sampling and survey campaigns are needed to reveal patterns of crust and mantle structure, geothermal heat flux, isostatic adjustment and dynamic topography, and rates of geomorphic change. For example, networks and surveys over West Antarctica would investigate the role of volcanism on evolving lithosphere, changing climate, and ice-sheet dynamics. Observations in East Antarctica are needed to better understand supercontinent assembly and break-up throughout Earth history.

The following infrastructure and logistics were deemed high priority to support geosciences research:

- Logistic hubs jointly supported by multiple nations and offering science opportunities to scientists from many nations. The logistic hubs would support air transport, ground traverses, and fuel depots. These in turn support work in the deep interior and coastal areas, sensor deployments, surveys, and drilling and sampling activities. Logistics hubs should be scalable according to the science requirements. Infrastructure and logistics requirements for the hubs include:
    - A variety of transport modes, for example ski-equipped aircraft and ground traverse capabilities, inter- and intra-continental.
    - Field camp support for field-team and transport personnel.
    - Deployment of fuel both at hubs and remote fuel caches.
    - Communications.
- Ice-breakers – Ice-breakers are essential for some ship-based activities, such as high-resolution bathymetry mapping and deep-sea drilling in ice-covered areas. They provide access to coastal research sites, and logistics support for interior stations/ logistic hubs.
- Polar research vessels – Polar research vessels provide access to coastal sites; enable deployment of AUVs, ROVs, sensor networks, and seabed drilling systems; and serve as platforms for coring/drilling and surveys of the marine environment. Ships capable of launching ROVs/AUVs in ice-infested waters may be needed.
- The geosciences community has a long history of successful application for ocean drilling ship time in the Southern Ocean through the International Ocean Discovery Program (IODP) and its predecessor programmes. This will continue to be an important mechanism to provide access to expensive drilling technologies, down-borehole instruments, and samples relevant to a wide range of research topics.

Life on the Precipice

Most of the highest-priority life sciences Horizon Scan questions can be addressed by access to areas where research is already undertaken. Therefore, access to Antarctic habitats, particularly terrestrial habitats, will not necessarily require extended logistics to support access to remote sites. The most important element of access is often not physical, but related to data (i.e. increased data-sharing). Other questions will require access to all regions of the Antarctic continent, the Southern Ocean, and sub-Antarctic islands. Current areas of high interest for life sciences researchers are:

- coastal regions of terrestrial Antarctica;
- the sub-Antarctic islands; and
- the deep sea.

There is a critical need to expand studies, currently mostly restricted to a relatively short summer season, to cover a much wider temporal range. This need will develop as understanding of the full season grows in significance. Improved deep-sea access is a high priority. Reliable access to terrestrial, freshwater, and marine environments is a key requirement for future Antarctic life sciences research. There is a pressing need to increase the understanding of the range and diversity of Antarctic terrestrial biota, which will require access to remote areas and specific habitats (such as intra- and sub-glacial ice habitats). Access to all areas is required, though coastal regions remain a priority for terrestrial work. Access to marine habitats has more-substantial requirements, which overlap substantially with the requirements of the physical sciences researchers (oceanographic, glaciological, and geological). Many of the Horizon Scan questions require extension of temporal access from seasonal to year-round, along with comprehensive access to all areas of the circum-continental oceans, including many that are currently difficult to access (sub-sea ice, sub-glacial, and sub-ice-shelf; deep marine).

To access these areas for life sciences research, the following infrastructure and logistics were deemed high priority:

- Improvement of modularity in facilities (mobile, collaborative).
- Coordination of existing ship and marine logistic operations.
- Extended temporal access (through winter) to Antarctic sites.
- Upgrade and enhancement of power delivery (in a renewable manner).
- Improved cleaning technologies for Antarctic research and support operations in both marine and terrestrial environments, in order to reduce contamination and the transfer of biological materials.

Automated sampling and robotic sampling will require development to extend reach both through time and across space. However, the presence of personnel in the field will remain essential. Marine infrastructure to provide access to ocean areas is essential, both at shallow sites, especially those that are under the permanent sea ice and ice shelves, and in the deep sea. Technologies utilised in deep-sea research elsewhere in the world can be learned from and adapted to the special circumstances of the Antarctic.

Other important issues identified by life sciences researchers include the following:

- A core requirement is for improved power technologies to extend the range and duration of deployed equipment and observatories. Power should be renewable as much as possible and should employ green technologies with minimal environmental impact.
- Protection of the intrinsic scientific value of study sites is essential. Procedures must be strictly adapted to limit the transfer of material or propagules among sites. This will require the provision of clean gear or cleaning technologies, from the scale of individuals through to ships, aircraft, and land vehicles.
- Improved collaboration and strategic sharing of resources will be essential to life sciences researchers, include the sharing of station facilities, and joint planning and coordination of logistics, including air operations.
- Access to high-performance computing and multi-"omics" platform infrastructure will be essential.

Near-Earth Space and Beyond – Eyes on the Sky

Antarctica is a unique place for observations of the Near-Earth Space and Beyond, and access requirements are related to: a) optimum placement of observatories, such as at South Pole Station; b) locations to launch high-altitude balloons; and c) other high plateau locations distant from disturbances. The ability to reach these often-remote areas (such as through air access to the high plateau), communications (wide bandwidth and continuous communication), and energy supplies for observatories to generate the tens of kilowatts of power needed for operation, are high-priority requirements. The greatest challenges to be faced are the ever-growing energy requirements and the need for greatly increased data transfer rates. For example, future neutrino experiments at South Pole are expected to need off-continent data transfer of 1,000 gigabytes per day (compared with150 today), while 24-hour coverage will be important for future Cosmic Microwave Background experiments.

- South Pole station – Electrical power and data-transfer rates are key challenges. As extended neutrino detector arrays are deployed, delivering hundreds of watts of power to the array stations up to 10 kilometres away remains problematic. As detectors grow to occupy areas of up to 1,000 square kilometres, autonomous power systems may provide the only solution.
- High plateau sites – Future logistic support of experiments on the high plateau might be done in a number of (non-exclusive) ways. Existing stations (Domes A, C, and F) can further develop their support capabilities; autonomous field observatories such as Ridge A might continue to grow as fully fledged robotic stations; and one or more new high-plateau sites could be developed.

Human Presence in Antarctica

Access requirements for addressing scientific questions in regard to the presence of humans in Antarctica parallel those of the life sciences, including:

- coastal regions of terrestrial Antarctica and the sub-Antarctic islands, particularly high-"intensity" sites (research and tourist);
- remote ice-free areas of the continent; and
- the maritime domain, with ships.

Understanding anthropogenic change relative to other change requires access both to current and new remote sites. Access needs can be met through current arrangements, though these may change as the spatial and temporal extent of science and tourism in the region changes. The requirements are essentially of an interactive form. Ongoing access by social science and humanity researchers to field sites is essential and can be done in coordination with other planned science and logistics activities. Access to high-impact sites and to new sites will be required in order to understand the ways in which changing patterns of activity in Antarctica are impacting the environment and how successful the various arrangements are in addressing these impacts. Access to the maritime domain is essential, as the highest volume of people access Antarctica by sea. Whether researchers are investigating biophysical or social sciences facets of research, tourism, or marine harvesting activities, access to the maritime domain is critical. For deep-sea impacts a range of autonomous vehicles as well as ship capability will continue to be required. Near-shore and benthic access across a range of areas remains essential**.** Enhanced collaboration between national Antarctic programmes, including logistics sharing, will be a hallmark of future Antarctic science. Equal opportunity for social sciences and humanities scholars to Antarctic field programmes and improvements will be essential in coordination of data collection, data storage, and access to information.

McMurdo Sound divers

Photo: S. Rupp, US National Science Foundation

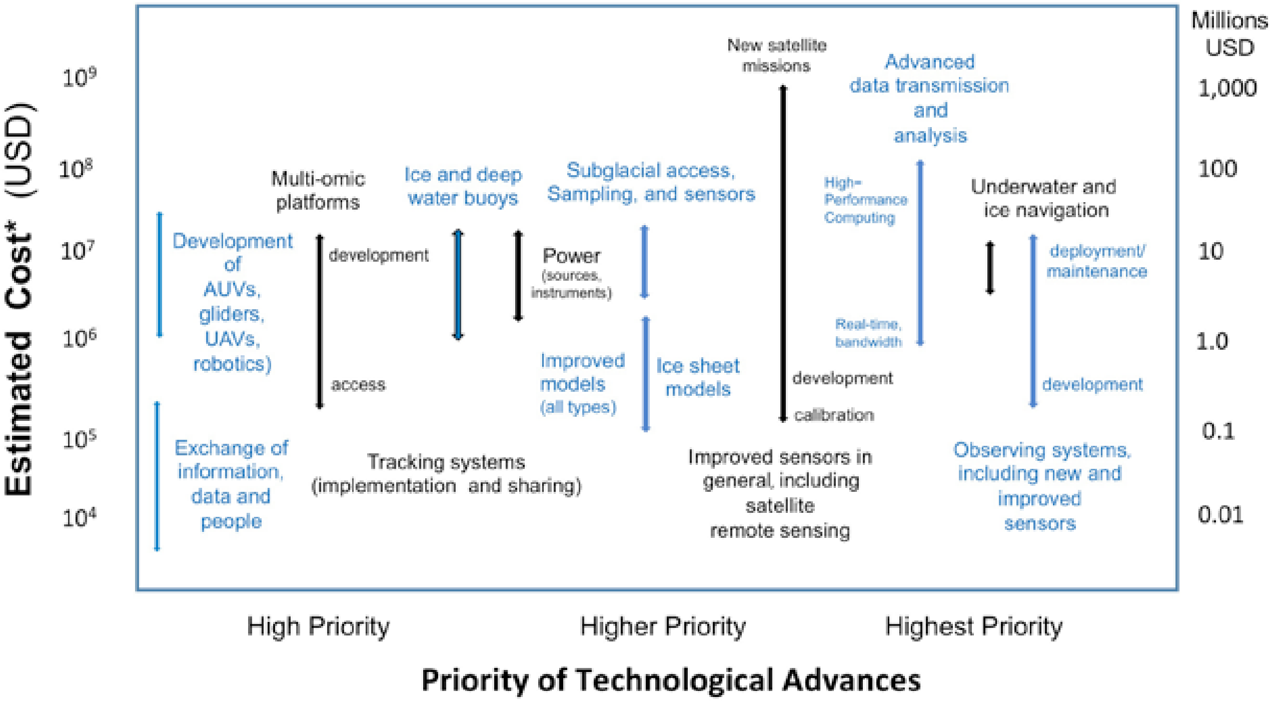
THE COST OF ANTARCTIC SCIENCE

There is a wide range in the available human and financial resources that national Antarctic programmes are allocated for investments in Antarctic technologies, access, logistics, and support efforts. While the overall expense of the requirements to realise the full potential of Antarctic science in the next two decades is great, there is a role for all interested parties to participate in ways that are commensurate with resources, expertise, and national interests. Even the largest national Antarctic programmes will by necessity set priorities and concentrate on those advancements judged to support the widest scientific community while offering the greatest potential scientific return on investment. No one country or programme has the wherewithal to simultaneously pursue all aspects of the highest-priority Antarctic science.

Listed from most costly (at top) to least costly (at bottom)	**to $10,000 USD**	**$10,000 to $100,000 USD**	**$100,000 to $500,000 USD**	**$500,000 to $1,000,000 USD**	**$1,000,000 to $10,000,000 USD**	**More than $10,000,000 USD**	**Total Responses**	**Don't know**
High-bandwidth networks	1%	3%	7%	6%	8%	9%	110	72
Oceanic sea-bed drilling/core-recovery technologies	1%	1%	3%	5%	17%	12%	107	66
Ice-sheet/ice-shelf drilling/core-recovery technologies	0%	2%	3%	6%	19%	13%	108	62
Ice-sheet and ice-shelf observatories	0%	3%	4%	6%	20%	11%	107	61
Remotely operated tethered and autonomous underwater vehicles with expanded sensor payloads	1%	4%	8%	6%	28%	4%	108	53
Integrated Earth System Models	1%	5%	2%	5%	20%	7%	108	65
On-site laboratories	4%	3%	10%	11%	18%	9%	109	49
Below-ice-sheet observing systems and the associated power and sensors requirements	0%	2%	7%	13%	16%	3%	116	68
Improved climate models	2%	7%	5%	8%	16%	9%	107	57
Subglacial sampling technologies	0%	0%	4%	6%	16%	8%	108	72
Calibration/validation of available satellite sensors	2%	8%	7%	7%	15%	4%	112	63
Deep-water and under-ice moorings and floats with tethered and/or wireless data transfer capabilities	1%	3%	2%	11%	14%	8%	108	66
Ice, sediment and rock down-borehole loggers and sensors	1%	6%	5%	15%	14%	2%	108	62
Remote weather stations with expanded and robust sensor arrays	1%	6%	12%	14%	13%	1%	108	57
Remote solid Earth sensor arrays – seismic, magnetic, etc.	0%	3%	5%	5%	12%	4%	107	77
Improved ecosystem models	2%	8%	6%	8%	12%	2%	108	67
Improved glaciological models	2%	6%	6%	8%	12%	2%	108	68
Continuous measuring sensors	1%	9%	14%	15%	10%	0%	110	57
Clean sampling technologies – chemical and biological	0%	6%	15%	11%	9%	1%	110	64
Improved geological models	2%	7%	6%	7%	7%	2%	108	73
Sampling handling and analysis techniques at *in situ* conditions (Temperature, Pressure)	2%	7%	12%	7%	7%	0%	107	71
Advanced "-omics" techniques	3%	5%	5%	2%	5%	0%	118	94
Advanced data analysis techniques	6%	11%	13%	12%	4%	1%	120	64

Table 3: Summary of results from ARC survey 1 of costs of highest priority technology requirements.

Figure 3: Summary of the qualitative estimates of the cost to develop high-priority technologies



*Cost estimates are order of magnitude over wide ranges, highly variable and dependent on the scope of the activity.

Summary of survey results indicating qualitative estimates of the cost to develop and make available a range of high-priority technologies judged to be essential to answering the highest-priority Antarctic scientific questions. *Horizontal bars with arrows indicate a range of possible costs which will be dependent on the scope and objectives of the development work undertaken. Costs will ultimately depend on finer delineation of the work involved by experts and these estimates are provided only as a general guide to the order of magnitude of the investment that may be involved. The survey results indicate a wide range of opportunities for investments in Antarctic science technologies commensurate with available resources and national interests.*

As can be seen from this assessment, a wide range of opportunities are presented with widely differing estimates of cost depending on the scope of the activity undertaken. At the lower-cost end of the spectrum (tens of thousands to hundreds of thousands of US dollars) is advanced handling and analysis techniques. At the higher end of the cost spectrum (tens of millions to hundreds of millions of US dollars) is permanent infrastructure, such as ships, stations and satellite missions. Other major technologies may require pooling of resources for greatest effect. It is abundantly clear that partnerships, sharing of facilities and technologies, and coordination of efforts will maximise investments. In some instances, the wished-for outcomes may be achievable by no other means. There are a number of models for countries to pool resources to accomplish what no single or few nations can accomplish (e.g. the IODP, ANDRILL, EPICA, CAML, POLENET, and IMCONet).

Technological advances in many cases will be incremental, building on what others have accomplished; thus, contributing to a larger effort may be most cost effective. An example is the development of sensors (here broadly defined): advances could be accomplished for modest targeted investments. Model development is also incremental, and advances can be made by individual scientists, culminating in broad application and assimilation.

These estimates suggest that there are abundant opportunities that are scalable to the resources available, allowing all countries and scientists to participate individually or as members of international teams. The exact design and scope of the various elements must be determined through detailed planning and expert assessments.

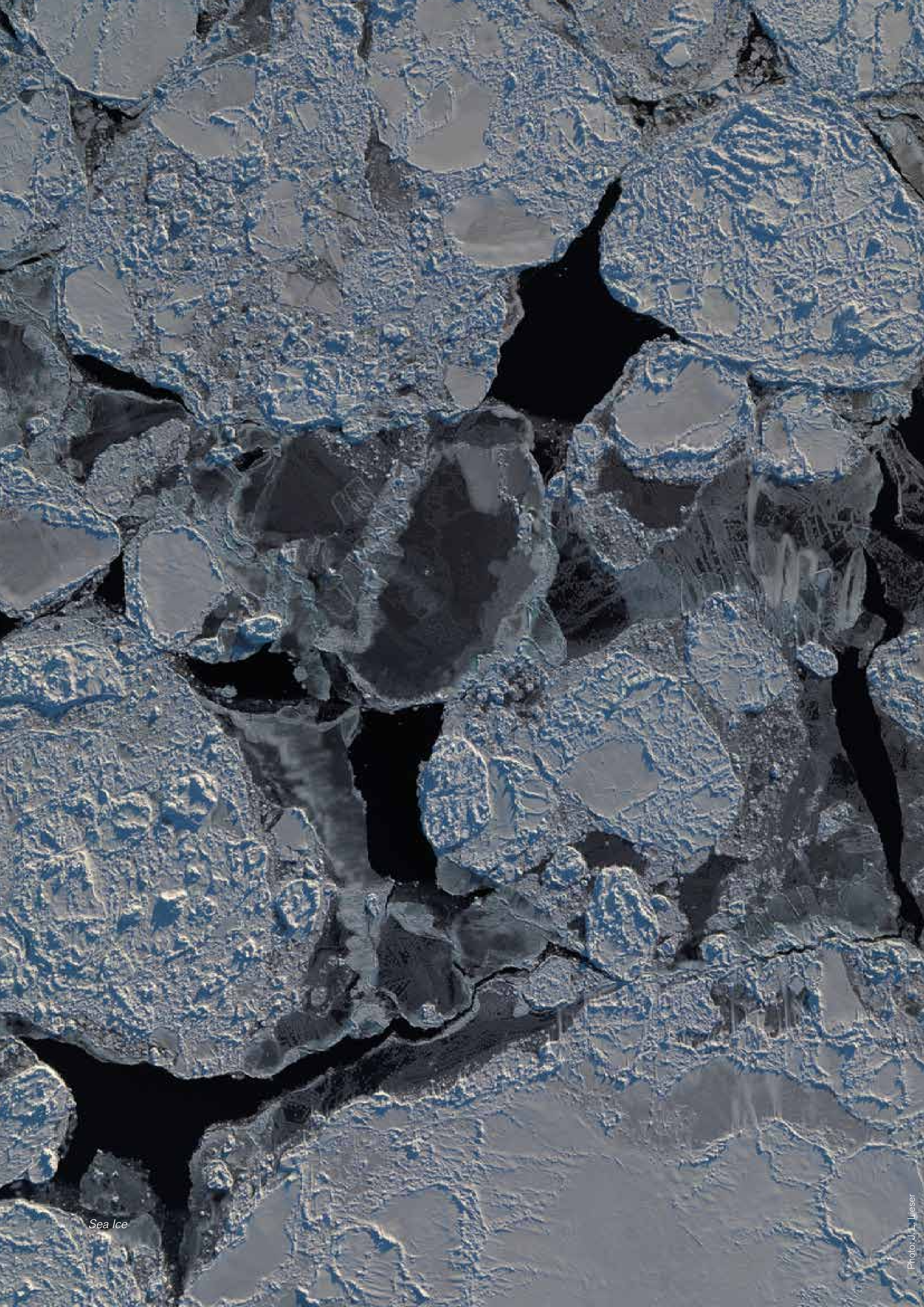
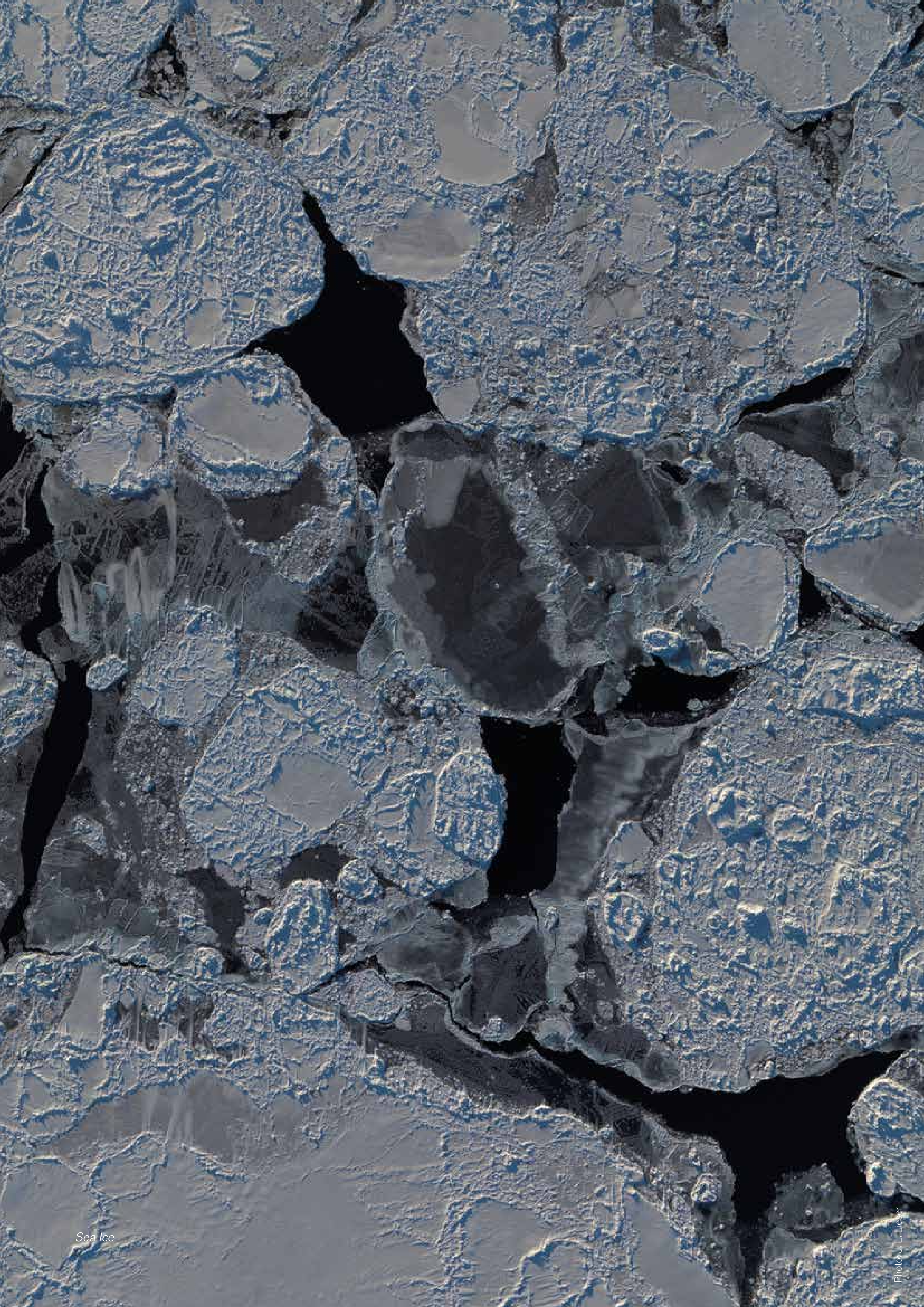

Sea Ice

Photo: J. L. Lieser



Sea Ice

Photo: J. L. Lieser

AN INTERNATIONAL COLLECTIVE

Consistently throughout discussions, international collaborations, sharing of knowledge and data, coordination of logistics, advancement of enabling technologies, optimising the utilisation of infrastructure, and focused partnerships were identified as indispensable if the full promise of Antarctic and Southern Ocean science is to be achieved in the twenty-first century. These conclusions transcended disciplinary scientific questions and interdisciplinary themes. There is wide recognition that the breadth and depth of Antarctic research make many of the wished-for outcomes beyond the capabilities of individual researchers and projects and, often, nations. The reality of finite and limited budgets and the necessity to bring talent and expertise to bear, regardless of location, are major drivers for working together for mutual benefit and greatest effect.

Photo: J. Tarnow, US National Science Foundation

The flags of the 12 original Antarctic Treaty signatory nations surround the ceremonial pole at Amundsen-Scott South Pole Station

There is much value to be gained through coordination and collaboration between disciplines. Infrastructure and logistics designed for one objective (e.g. sub-sea-ice marine water surveys) should be adapted and broadened to accomplish other objectives (e.g. biological surveys). Communication between the polar community and national space agencies and the remote sensing community is vital for improving and creating new satellite sensors, applications, and observations. Cooperation among national providers is key to accomplish "big science" and for expanding access to remote regions. Greater collaboration (such as in addressing communications and information technology challenges) with external agencies (e.g. commercial and other governmental organisations) will be critical to developing and applying new technologies. Enhanced collaboration must include improved data sharing and more-open access to stations, logistics, and operational activities. It was deemed important to balance the differential skills, capabilities, and capacities across different national programmes, particularly in fast-developing and technology-intensive research sectors through researcher-exchange programmes and capacity building. "Super sites" of high scientific interest were recommended as locations where the community could come together and establish the framework for multi- and cross-disciplinary science to be conducted. These sites would create synergy and cost-effectiveness by measuring and observing a wide range of variables within a synoptic and holistic study design. Related to this was the creation of logistic hubs and interoperable nodes that could support a range of sensors and provide the necessary cyber-infrastructure for communications and data collection and transmission. Within this mix was a call for mobile facilities of various types that could be deployed to support projects beyond the reach of permanent stations, with an ability to rapidly deploy to take advantage of time-sensitive opportunities.

An important emerging trend over the last decade or more is regional alliances of national Antarctic programmes. These alliances promote regional-based partnerships that share values and cultures and often allow scientists to communicate in their first language.

Concordia accumulation stick measurements

Photo: V. Favier, IPEV

TWENTY-FIRST CENTURY ANTARCTIC SCIENCE

Historically, the Antarctic science community has been adept at "big science" projects that involve tens of investigators and multiple scientists across diverse disciplines and nations. These types of projects and programmes were epitomised by the portfolio of projects that delivered the International Polar Year 2007–2008. This will remain a hallmark of Earth System and Antarctic Science in the twenty-first century. The scientific questions being asked are complex, and global-, continent-, and ocean-wide in scope and reach. However, individual scientists and small groups of scientists working on narrower, targeted topics are important incubators of new ideas, innovation, and cutting-edge science. These directed studies are an important component of the international Antarctic scientific enterprise, which needs to be maintained while "big science" is pursued.

The highest-priority needs to enable the research necessary to address the ambitious scientific agenda posed by the SCAR Horizon Scan can be considered as two types: "upstream", the collection of a wide and diverse set of observations, samples, and data; and "downstream", what happens once observations, samples, and data are collected. Each of these activities has significant challenges and ramifications for how Antarctic and Southern Ocean science is conducted and supported.

In the "downstream", a wide range of technologies are needed to retrieve, process, preserve, and move data and samples from the remote field to locations where scientists can process the materials on the continent, on ships, and/or at home institutions. As is true globally, the trend is for greater automation through unmanned and robotic platforms equipped with an array of existing and yet-to-be-developed sensors. A critical underpinning technology of these efforts is the need for development of power supplies that extend the duration and frequency of sampling periods and allow year-round deployment and access to all of the southern Polar Region. The make-up of this downstream "tool kit" has wide-ranging ramifications for the required infrastructure and logistics. "Downstream" requirements to answer the highest-priority scientific questions entail much greater access in the future to deliver continent- and ocean-wide observations and samples at high frequency throughout the year.

The "upstream" requirements also face significant challenges as the scientific enterprise evolves and becomes more complex. Most of these challenges are related to transmission and processing of "big data sets" of widely varying types and volumes. Computational capacity is essential to assimilating observations and data into numerical models. Access to adequate cyber-infrastructure and high-performance computing will be essential. Data transmission and communications technologies must take advantage of the latest developments in these fast-changing sectors to optimise the productivity of time on the ground in the Antarctic. At the core of the "upstream" requirements is open and easy access to data of all kinds. These requirements highlight one challenge that was not explicitly considered by ARC but that is important: the availability of a qualified, technical workforce at all levels from field support to home-base laboratories.

The promise of future knowledge and insight to be gained by studying and understanding the Antarctic region has never been greater.

The Earth System and how it has and will respond to anthropogenic stressors can be understood and predicted only with an improved understanding of Antarctica and the Southern Ocean.

- The highest-priority technological requirements are enhanced observing systems of all kinds, improved Earth System Models, new and improved access to satellites and sensors, and expanded spatial and temporal discrete sampling efforts region-wide.
- Much of Antarctic research is field-based and will continue to be for the foreseeable future; therefore, access is often a critical limiting step in conducting research.
- Expanded continent- and ocean-wide access year-round is essential, including to areas of high scientific interest, and "super sites" should be established for collaborative, interdisciplinary research.
- Observatory platforms need to be interoperable and capable of supporting a diverse array of interoperable sensors that support many differing disciplines to allow interdisciplinary, synoptic collection of data.
- Major challenges are associated with collecting, transmitting, and analysing "big data sets"; adequate bandwidth and transfer rates must be solved both "down-stream" and "up-stream".
- Meeting the power requirements for a wide range of technologies is a critical challenge that will require improved power capacity and lower-energy-consumption equipment designs.
- Greater automation will lessen dependency on permanent infrastructure but will require technologies that expand the spatial range and temporal duration of deployments. However, inter- and intra-continental infrastructure remains foundational (ships, stations, aircraft, traverses, deep field camps, etc.).
- Scientific advances are critically dependent on the improved exchange of people and information, logistic coordination, technology transfer and dissemination, and availability of data and computing power.
- To take advantage of existing and new technologies, the Antarctic community must interact with mainstream science communities and agencies and programmes that provide critical enabling capabilities.

Photo: Japan's National Institute of Polar Research (NIPR)

Dome Fuji ice core drilling, JARE47

Technological advances within and beyond Antarctica are not only critical to answering high-priority scientific questions; they can also fundamentally change what questions are addressable, and even what scientific questions can be asked (for example, the advent of space-based science fundamentally changed our view of the planet). As a geographically focused community, polar scientists must be vigilant in keeping abreast of developments in mainstream science – particularly on the technological front. It is a challenge to bring to bear what others have learned elsewhere, and a lack of doing so diminishes the justifications for Antarctic science, which may be seen as isolated or out of touch with developments elsewhere. In a number of critical areas, such as satellite remote sensing, development of sensors and automated and robotic platforms, computing and information technologies, and advances in power technologies, it is expected that advances will occur outside of the Antarctic community. If it is to remain relevant, the community needs to be ever vigilant and must capitalise on advances in mainstream science through their application to the research conducted in the Polar Regions.

The availability and production of "big data" is a modern scientific phenomenon that has wide-ranging implications, and this massive flow of data can be optimally utilised only by applying the latest technologies in information, communications, and computation. Because of the remoteness of Polar Regions there are special challenges to addressing these issues there.

The ultimate controlling factor is the availability of financial resources to conduct science, and recent pressures on the national Antarctic programmes make international coordination and cooperation not only an aspiration but a necessity. In addition, expertise, innovation, and insight know no national boundaries and the collective is stronger than the individual. Access restrictions, which are an outflow of financial limitations, are a critical limiting step geographically and temporally, and new ways to partner and cooperate to overcome access issues will be essential for optimising scientific return on investments. Communicating the relevance and necessity of science conducted in the Antarctic will continue to be essential in the competition of ideas within the context of increasing demands on limited resources worldwide.

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Wind turbines at Crater Hill wind farm, Ross Island

Photo: P. Reynolds, Antarctica New Zealand Pictorial Collection: K242 12/13

APPENDICES

Appendix 1:
ARC SURVEY 1

Opened on-line on 20 March 2015; Closed 31 May 2015; Powered by Qualtrics software.

453 people begun the survey; 230 of those completed the survey in full; 223 completed a portion of the survey. All responses are considered even in the case that the survey was not entirely completed.

SECTION 1: The Demographics of Respondents

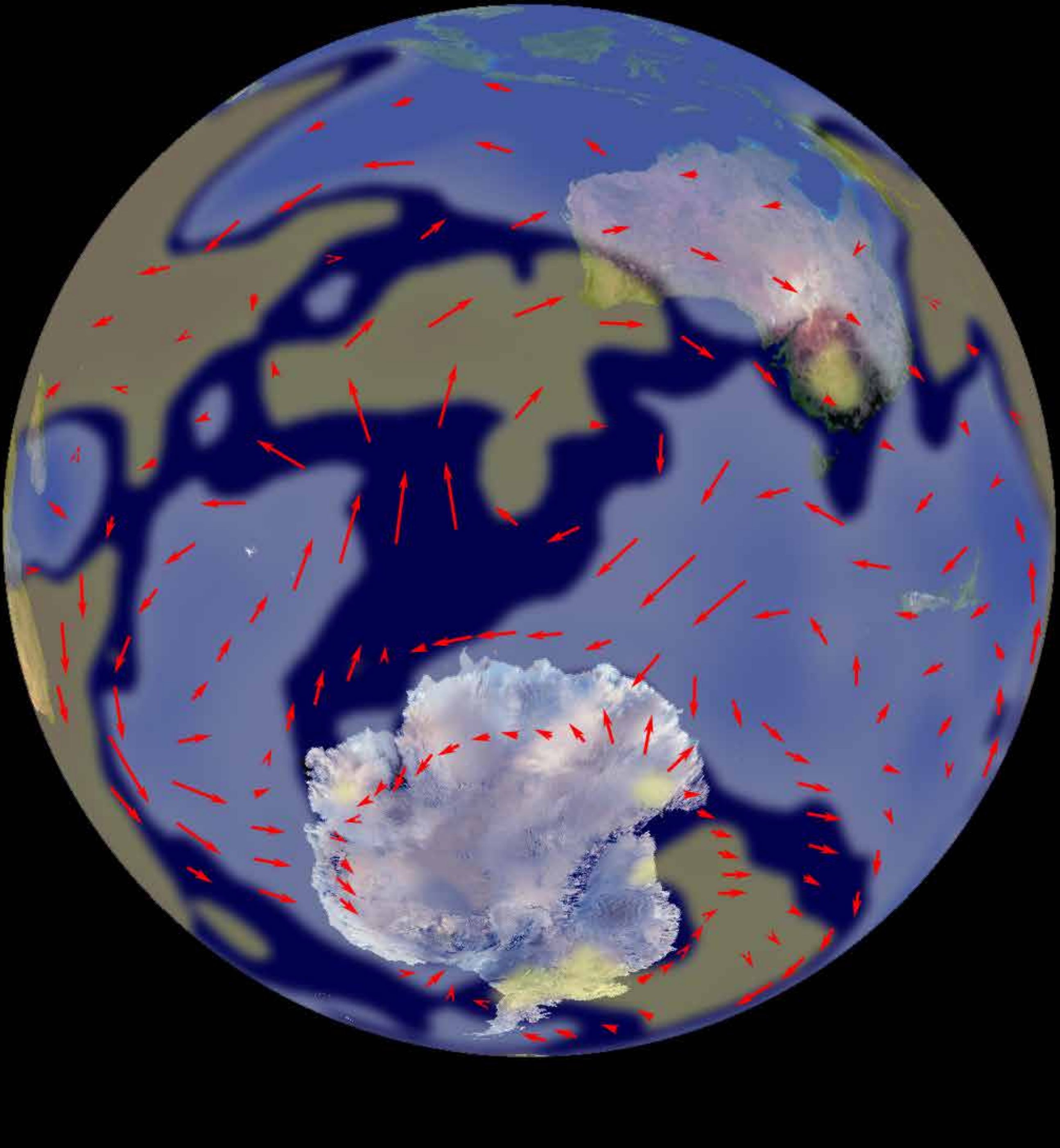
Gender: 33% female, 65% male and 2% chose not to respond

Country of residence for majority of year:

14%	United Kingdom	10%	United States	10%	New Zealand
9%	Australia	7%	France	6%	Chile
4%	Germany	4%	Japan	4%	Republic of Korea
3%	Argentina	3%	India	3%	Brazil
2%	Italy	2%	Belgium	2%	Spain
2%	Norway	2%	Sweden	1%	Portugal
1%	China	1%	Uruguay	1%	Switzerland
1%	Venezuela	1%	Russia		
<1% each	Afghanistan, Belarus, Bosnia and Herzegovina, Bulgaria, Canada, Czech Republic, Denmark, Estonia, Ireland, Malaysia, Netherlands, Peru, Poland, South Africa, Ukraine				

In what capacity are you responding to this survey?

65%	Scientist/Researcher	**6%**	National Antarctic Program Manager	6%	Graduate Student
Those 65% were asked two additional questions:		**4%**	National Antarctic Program Support Person	4%	Postdoctoral Appointee
1) Which of the SCAR groups most closely align with your interests?		**1%** each	Medical Doctor, Engineer, Technician, Logistician	3% each	Interested Citizen, Other
39%	Geosciences	Those **14%** were asked one additional question:		2% each	Undergraduate Student, Policy maker
38%	Life Sciences	**1) Are you a member of any of the COMNAP Expert Groups?**		1% each	Educator, Science Funder, Prefer not to respond
26%	Physical Sciences	54%	No		
3%	Social Sciences/ Humanities	17%	Environment		
2) Select the discipline or topic which most closely aligns with your area of research:		11%	Education and Outreach		
9% each	Biodiversity, Glaciology	9%	Energy & Technology		
8%	Ecology	9%	Training		
6% each	Biological Oceanography /Marine Biology, Biology, Atmospheric Science	6%	Safety		
5% each	Geology, Birds & Marine mammals, Physical Oceanography	6%	Air		
4% each	Cryosphere, Geophysics, Paleoclimate	6%	Medical		
3% each	Ice Core Science, Ocean Observing	3%	Shipping		
2% each	Astronomy & Astrophysics, Geological Oceanography, Climate Science, Chemical Oceanography, Sea Ice				
1% each	Geodesy, Law/Governance, Remote Sensing, Humanities, Meteorology, Genetics, Near Earth Space Science, Conservation/Environmental Science				



Atmospheric moisture and wind patterns from meteorological data, for years with high snowfall at Law Dome (red circle). Blue shades are areas with above average moisture in the atmosphere, tan areas depict below-average moisture and red arrows show how the wind deviates from its normal direction. The map shows moist air being transported south to East Antarctica and Law Dome, accompanied by dry air flowing northward to Western Australia. (From van Ommen, T. D. & Morgan, V. (2010.) Snowfall Increase in Coastal East Antarctica Linked with Southwest Western Australian Drought. Nature Geosciences, 3, 267–272.)

Photo: Tas van Ommen, Australian Antarctic Division

SECTION 2: Technology Requirements by Horizon Scan Cluster

HORIZON SCAN CLUSTER 1:

Antarctic Atmosphere and Global Connections

"Changes in Antarctica's atmosphere alter the planet's energy budgets, temperature gradients, and air chemistry and circulation. Too little is known about the underlying processes. How do interactions between the atmosphere, ocean and ice control the rate of climate change? How does climate change at the pole influence tropical oceans and monsoons? How will the recovering ozone hole and rising greenhouse-gas concentrations affect regional and global atmospheric circulation and climate"
Kennicutt et al., 2014 *Nature* COMMENT

HSC1Q1: How is climate change and variability in the high southern latitudes connected to lower latitudes including the Tropical Ocean and monsoon systems?

HSC1Q2: How do Antarctic processes affect mid-latitude weather and extreme events?

HSC1Q3: How have teleconnections, feedbacks, and thresholds in decadal and longer term climate variability affected ice sheet response since the Last Glacial Maximum, and how can this inform future climate projections?

HSC1Q4: What drives change in the strength and position of Westerly winds, and what are their effects on ocean circulation, carbon uptake and global teleconnections?

HSC1Q5: How did the climate and atmospheric composition vary prior to the oldest ice records?

HSC1Q6: What controls regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean?

HSC1Q7: How can coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) be better represented in weather and climate models?

HSC1Q8: Does past amplified warming of Antarctica provide insight into the effects of future warming on climate and ice sheets?

HSC1Q9: Are there CO2 equivalent thresholds that foretell collapse of all or part of the Antarctic Ice Sheet?

HSC1Q10: Will there be release of greenhouse gases stored in Antarctic and Southern Ocean clathrates, sediments, soils, and permafrost as climate changes?

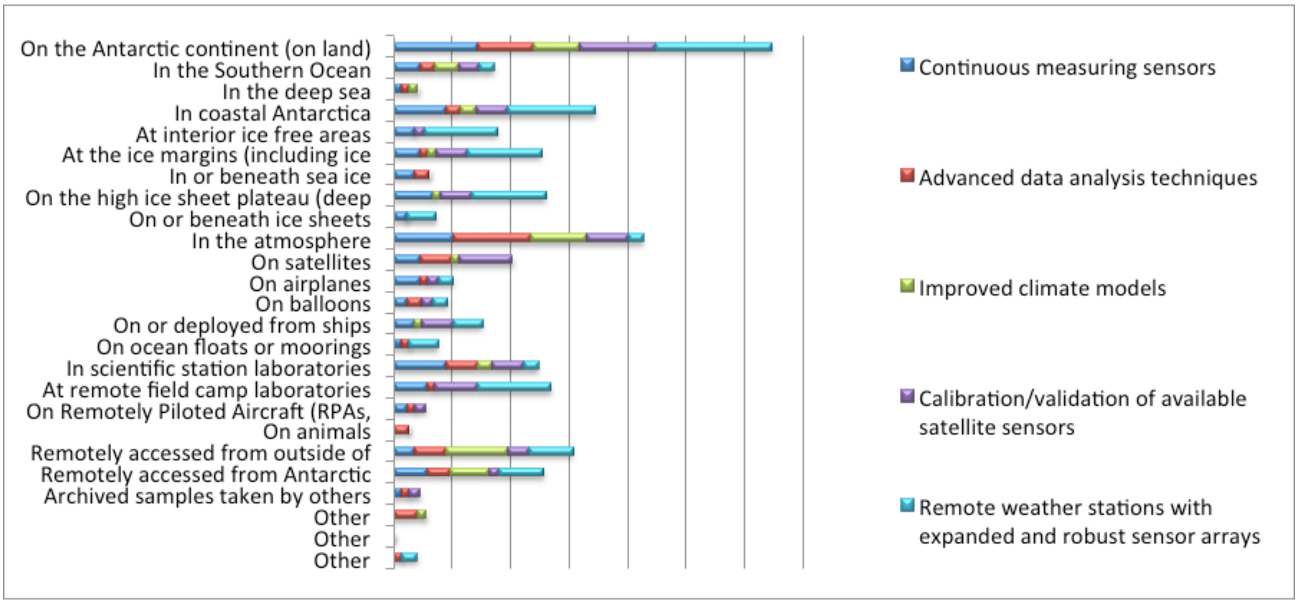
HSC1Q11: Is the recovery of the ozone hole proceeding as expected and how will its recovery affect regional and global atmospheric circulation, climate and ecosystems?

Antarctic Roadmap Challenges Survey 1

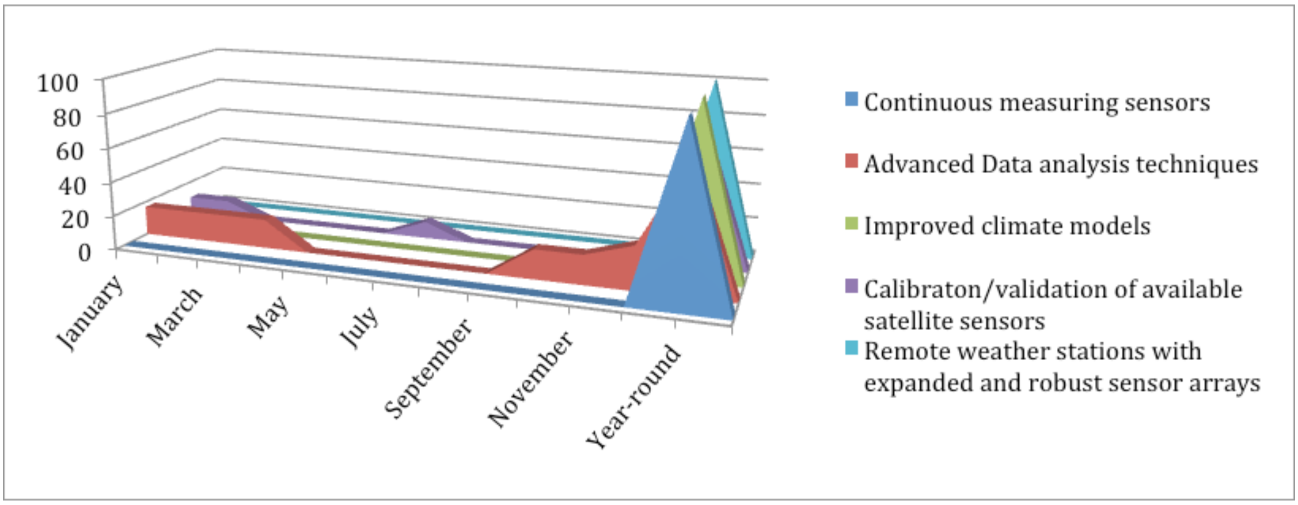
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top five)	Q: Does this technology currently exist?	Q: Is this technology available to you?
43% N=25	Continuous measuring sensors	75% yes; 25% no	58% yes; 42% no
38% N=22	Advanced data analysis techniques	100% yes	36% yes; 55% no; 9% yes-in collaboration
33% N=19	Improved climate models	50% yes; 43% no; 7% don't know	14% yes; 86% no
26% N=15	Calibration/validation of available satellite sensors	80% yes; 10% no; 10% partly	50% yes; 38% no; 13% partly
26% N=15	Remote weather stations with expanded and robust sensor arrays	87% yes; 13% no	14% yes; 86% no

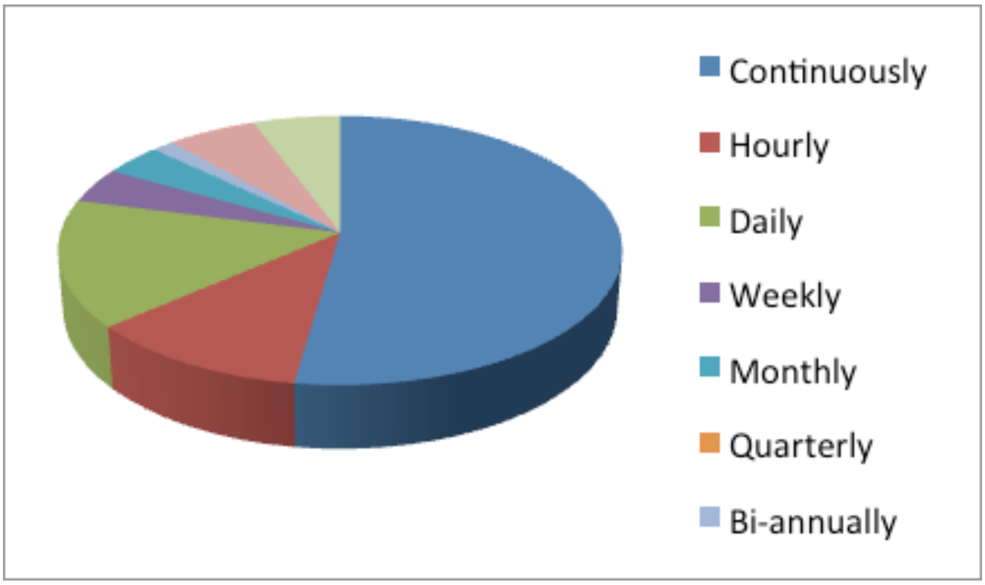
Q: In what setting would this technology be used?



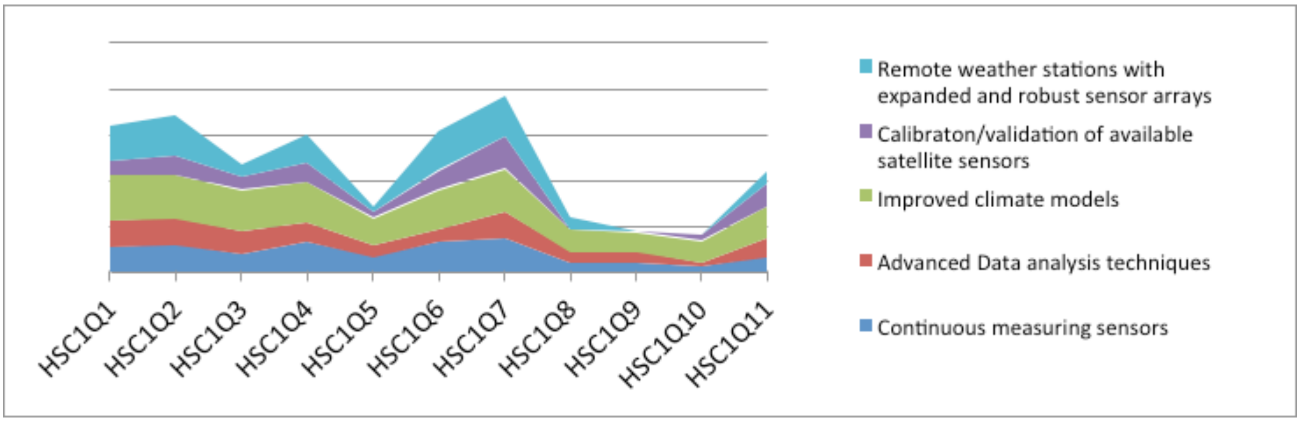
Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 1 questions does this technology specifically apply to?



L'Astrolabe passage through sea ice

Photo: P. Apelt, IPEV

HORIZON SCAN CLUSTER 2:

Southern Ocean and Sea Ice in a Warming World

"The Antarctic ice sheet contains about 26.5 million cubic kilometres of ice, enough to raise global sea levels by 60 metres if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown."
Kennicutt et al., 2014 *Nature* COMMENT

HSC2Q12: Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change?

HSC2Q13: Why are the properties and volume of Antarctic Bottom Water changing, and what are the consequences for global ocean circulation and climate?

HSC2Q14: How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing?

HSC2Q15: What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice?

HSC2Q16: How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean?

HSC2Q17: How has Antarctic sea ice extent and volume varied over decadal to millennial time scales?

HSC2Q18: How will changes in ocean surface waves influence Antarctic sea ice and floating glacial ice?

HSC2Q19: How do changes in sea ice extent, seasonality and properties influence Antarctic atmospheric and oceanic circulation?

HSC2Q20: How do extreme events affect the Antarctic cryosphere and Southern Ocean?

HSC2Q21: How did the Antarctic cryosphere and the Southern Ocean contribute to glacial-interglacial cycles?

HSC2Q22: How will climate change affect the physical and biological uptake of CO2 by the Southern Ocean?

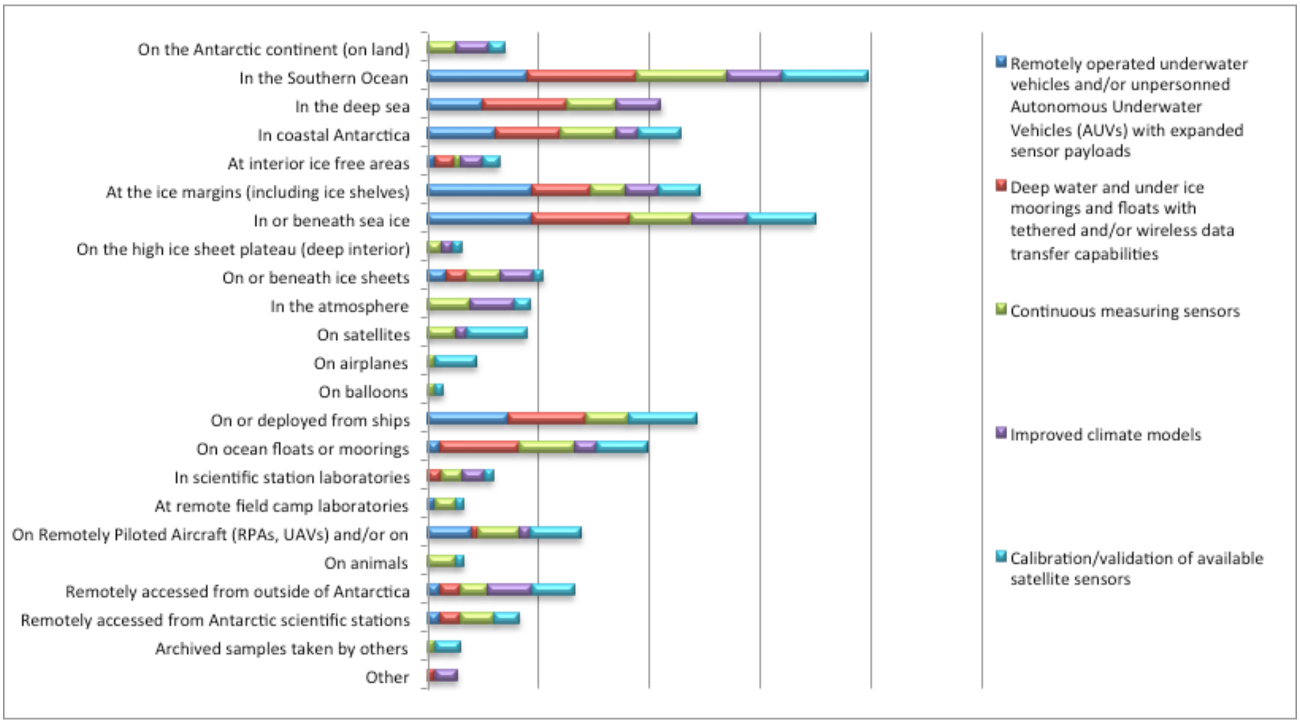
HSC2Q23: How will changes in freshwater inputs alter ocean circulation and ecosystem processes?

Antarctic Roadmap Challenges Survey 1:

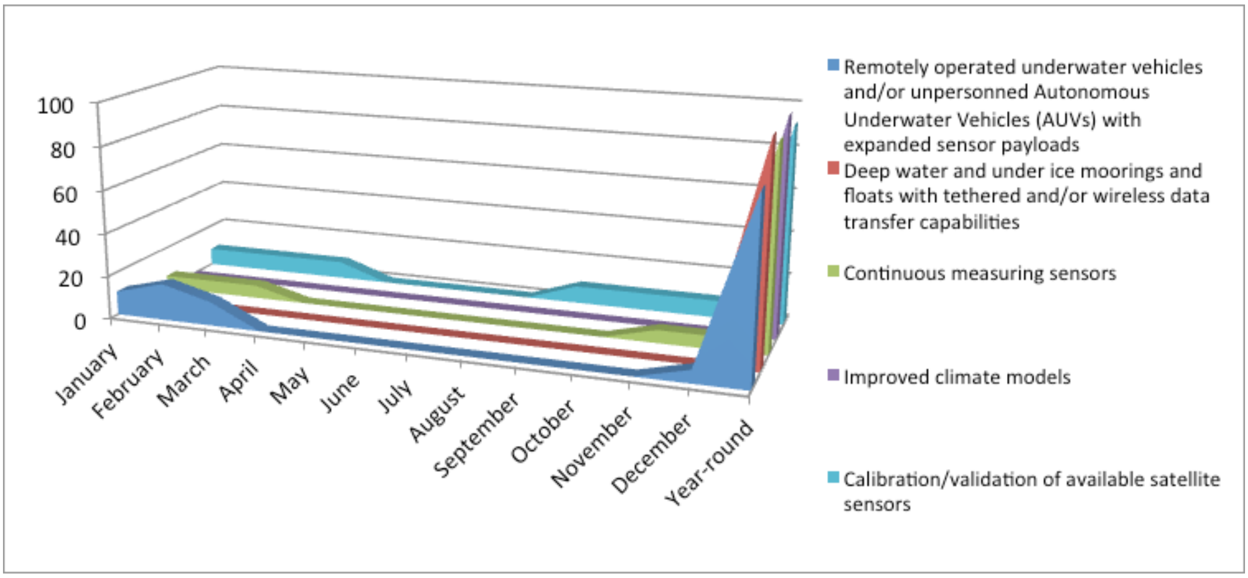
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top five)	Q: Does this technology currently exist?	Q: Is this technology available to you?
43% N=20	Remotely operated underwater vehicles and/or unpersonned Autonomous Underwater Vehicles (AUVs) with expanded sensor payloads	76% yes; 12% no; 12% partly	33% yes; 67% no
41% N=19	Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	73% yes; 7% no; 20% partly	36% yes; 64% no
41% N=19	Continuous measuring sensors	88% yes; 6% no; 6% partly	86% yes; 14% no
37% N=17	Improved climate models	60% yes; 40% no	50% yes; 25% no; 25% uncertain
33% N=15	Calibration/validation of available satellite sensors	92% yes; 8% no	80% yes; 20% no

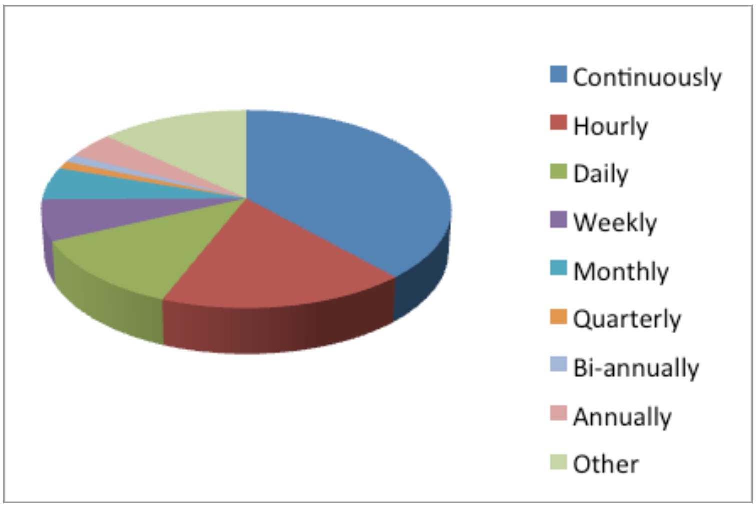
Q: In what setting would this technology be used?



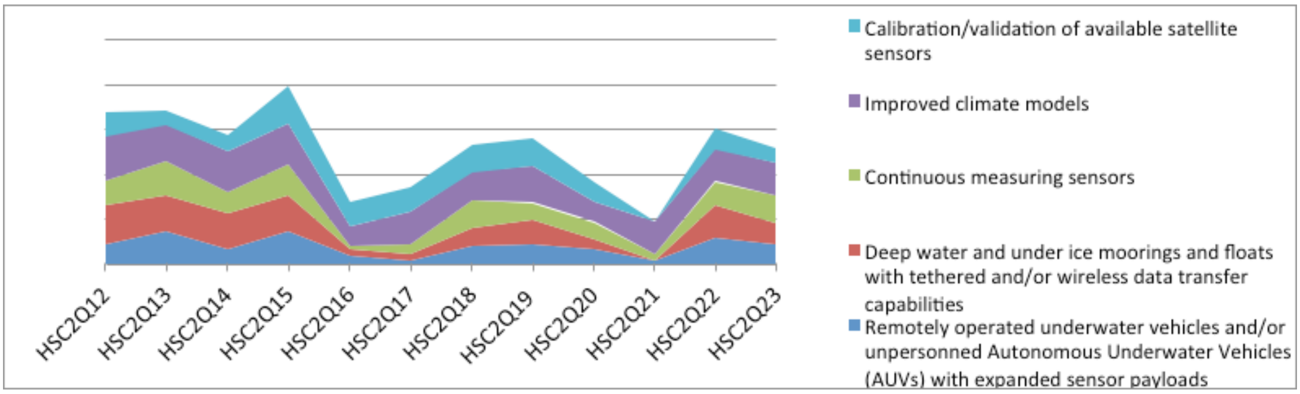
Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 2 questions does this technology specifically apply to?



Microbiologist gathering data, with Marguerite Bay, Antarctic Peninsula, in the background

Photo: E. Barticevic, INACH

HORIZON SCAN CLUSTER 3:
Antarctic Ice Sheet and Sea Level

"The Antarctic ice sheet contains about 26.5 million cubic kilometers of ice, enough to raise global sea levels by 60 meters if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown."
Kennicutt et al., 2014 *Nature* COMMENT

HSC3Q24: How does small-scale morphology in subglacial and continental shelf bathymetry affect Antarctic ice sheet response to changing environmental conditions?

HSC3Q25: What are the processes and properties that control the form and flow of the Antarctic ice sheet?

HSC3Q26: How does subglacial hydrology affect ice sheet dynamics, and how important is it?

HSC3Q27: How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability?

HSC3Q28: What are the thresholds that lead to irreversible loss of all or part of the Antarctic ice sheet?

HSC3Q29: How will changes in surface melt over the ice shelves and ice sheet evolve, and what will be the impact of these changes?

HSC3Q30: How do oceanic processes beneath ice shelves vary in space and time, how are they modified by sea ice, and do they affect ice loss and ice sheet mass balance?

HSC3Q31: How will large-scale processes in the Southern Ocean and atmosphere affect the Antarctic ice sheet, particularly the rapid disintegration of ice shelves and ice sheet margins?

HSC3Q32: How fast has the Antarctic ice sheet changed in the past and what does that tell us about the future?

HSC3Q33: How did marine-based Antarctic ice sheets change during previous inter-glacial periods?

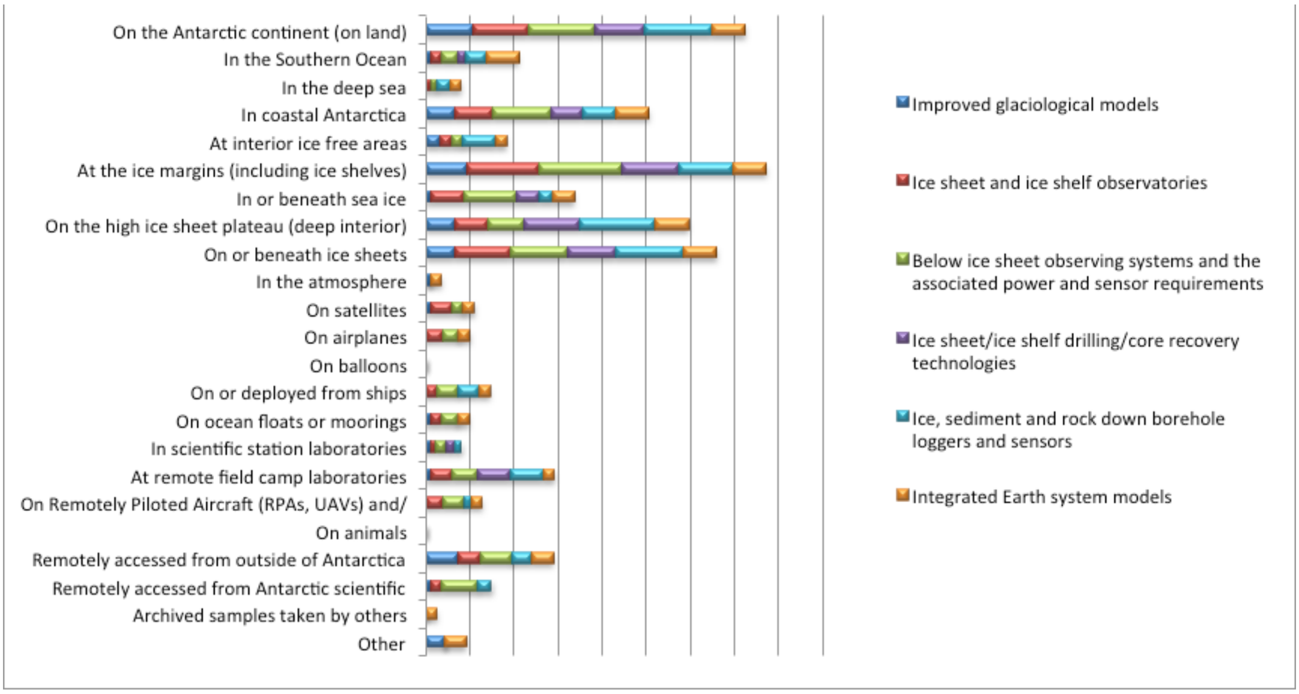
HSC3Q34: How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice?

Antarctic Roadmap Challenges Survey 1:

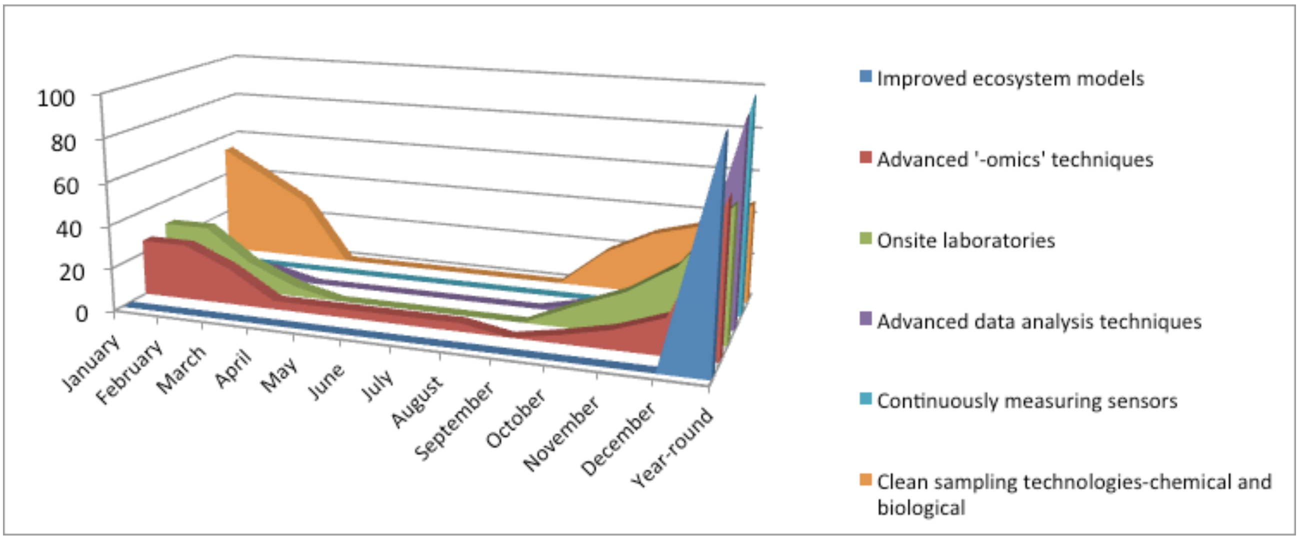
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

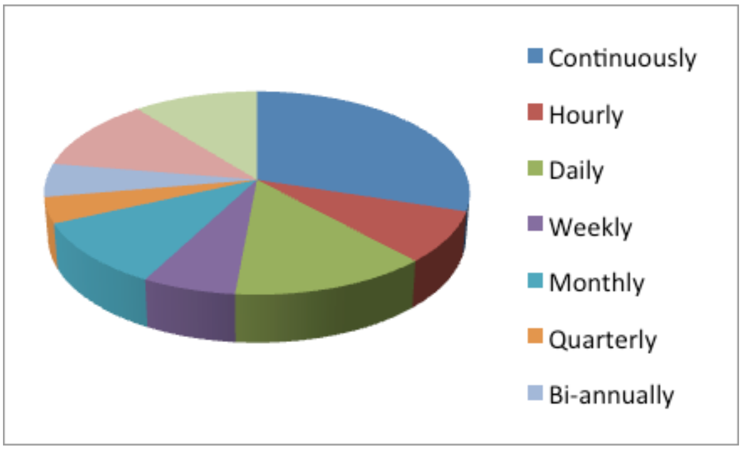
	(top six)	Q: Does this technology currently exist?	Q: Is this technology available to you?
45% N=23	Improved glaciological models	61% yes; 33% no; 6% partly	73% yes; 27% no
35% N=18	Ice sheet and ice shelf observatories	60% yes; 40% no	50% yes; 50% no
31% N=16	Below ice sheet observing systems and the associated power and sensor requirements	50% yes; 40% no; 10% partly	20% yes; 80% no
25% N=13	Ice sheet/ice shelf drilling/core recovery technologies	100% yes	64% yes; 27% no; 9% partly
24% N=12	Ice, sediment & rock down borehole loggers & sensors	44% yes; 44% no; 11% partly	25% yes; 50% no; 25% partly
22% N=11	Integrated Earth system models	83% yes; 17% no	25% yes; 75% no

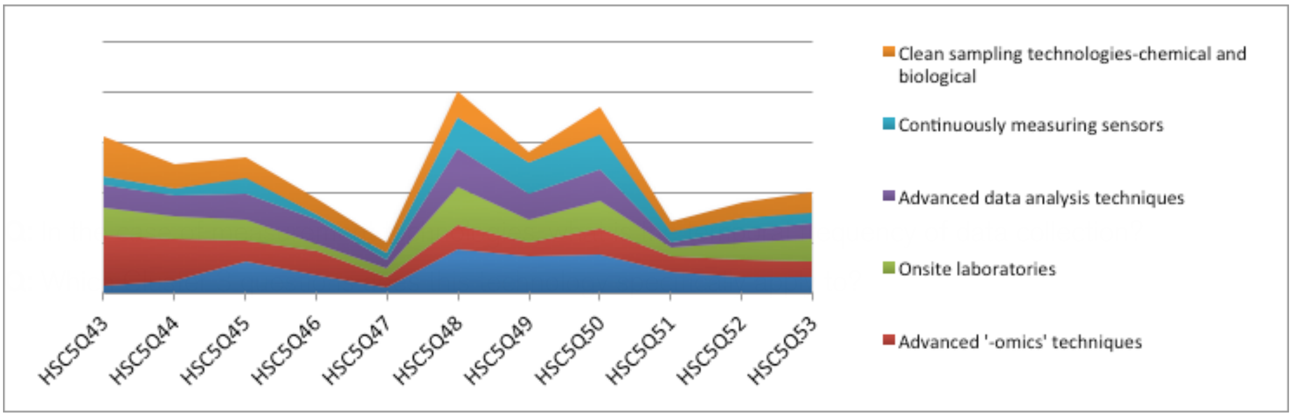
Q: In what setting would this technology be used?

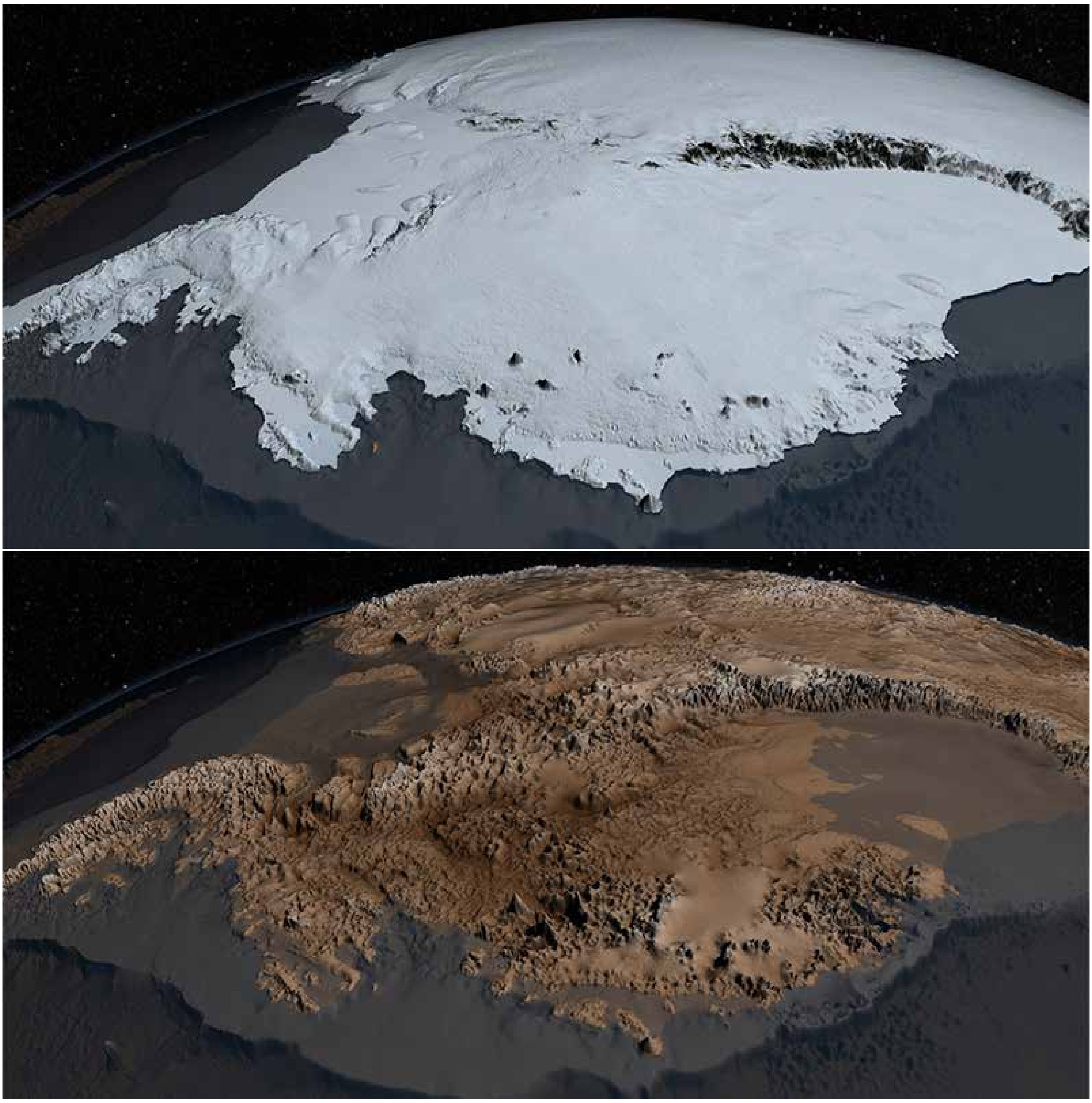


Q: In which months of the year would this technology be used?









Images: NASA's Goddard Space Flight Center and Peter Fretwell, Mapping & Geographic Information Centre, British Antarctica Survey

Bedmap2: Bedrock Topology of Antarctica. This image depicts the differences between Antarctica's ice sheet, top, with its underlying topography. The map, produced by the British Antarctic Survey, illustrates the frozen continent with a level of clarity and resolution never before available, including a look at the mountain landscapes buried in ice and valleys that run deeper than previously known.

HORIZON SCAN CLUSTER 4:

Dynamic Earth – Probing Beneath Antarctic Ice

“Reveal Antarctica’s history. Glimpses of the past from rock records collected around the continent’s margins suggest that Antarctica might look markedly different in a warmer world. But rocks from the heart of the continent and the surrounding oceans have been only sparsely probed. Responses of the crust to, and the effects of volcanism and heat from Earth’s interior on, overlying ice are largely undescribed. We know little about the structure of the Antarctic crust and mantle and how it influenced the creation and break-up of super-continents. Ancient landscapes beneath ice reveal the history of interactions between ice and the solid Earth. Geological signatures of past relative sea level will show when and where planetary ice has been gained or lost. We need more ice, rock and sediment records to know whether past climate states are fated to be repeated.”
Kennicutt et al., 2014 *Nature* COMMENT

HSC4Q35: How does the bedrock geology under the Antarctic ice sheet inform our understanding of supercontinent assembly and break-up through Earth’s history?

HSC4Q36: Do variations in geothermal heat flux in Antarctica provide a diagnostic signature of sub-ice geology?

HSC4Q37: What is the crust and mantle structure of Antarctica and the Southern Ocean, and how do they affect surface motions due to glacial isostatic adjustment?

HSC4Q38: How does volcanism affect the evolution of the Antarctic lithosphere, ice sheet dynamics, and global climate?

HSC4Q39: What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes?

HSC4Q40: How do tectonics, dynamic topography, ice loading and isostatic adjustment affect the spatial pattern of sea level change on all timescales?

HSC4Q41: Will increased deformation and volcanism characterize Antarctica when ice mass is reduced in a warmer world, and if so, how will glacial- and ecosystems be affected?

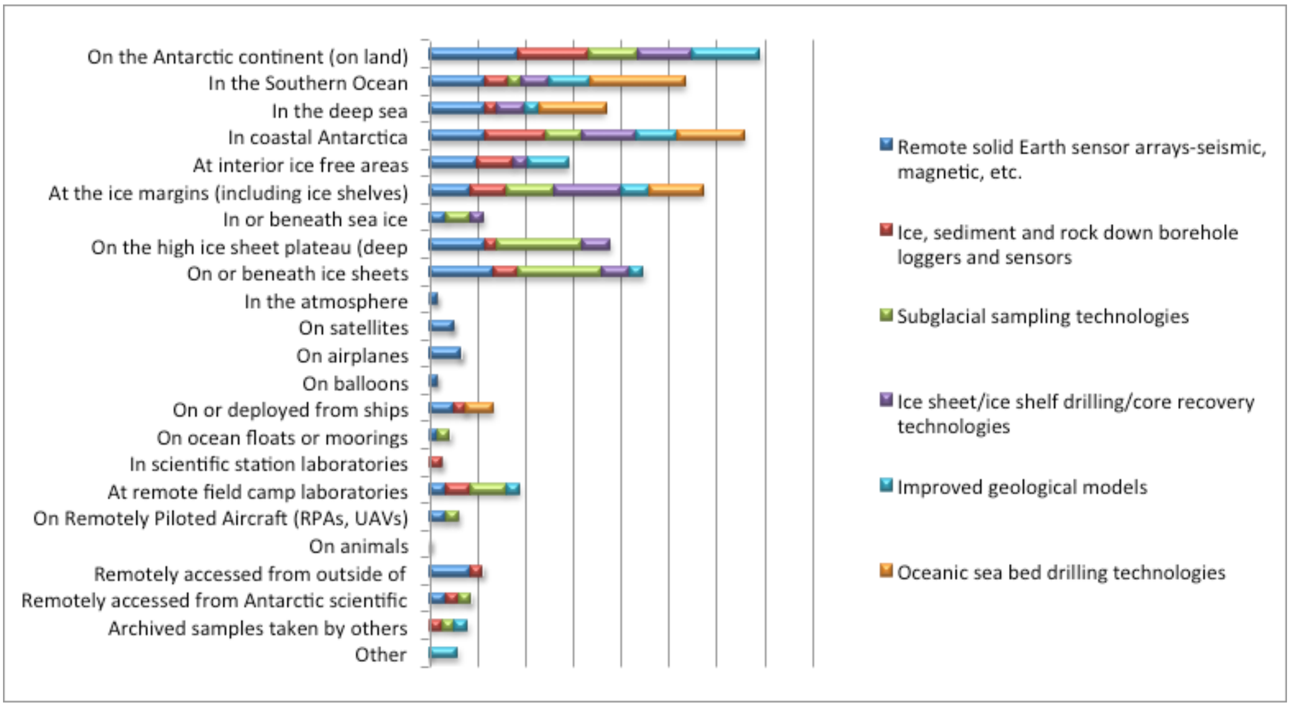
HSC4Q42: How will permafrost, the active layer and water availability in Antarctic soils and marine sediments change in a warming climate, and what are the effects on ecosystems and biogeochemical cycles?

Antarctic Roadmap Challenges Survey 1:

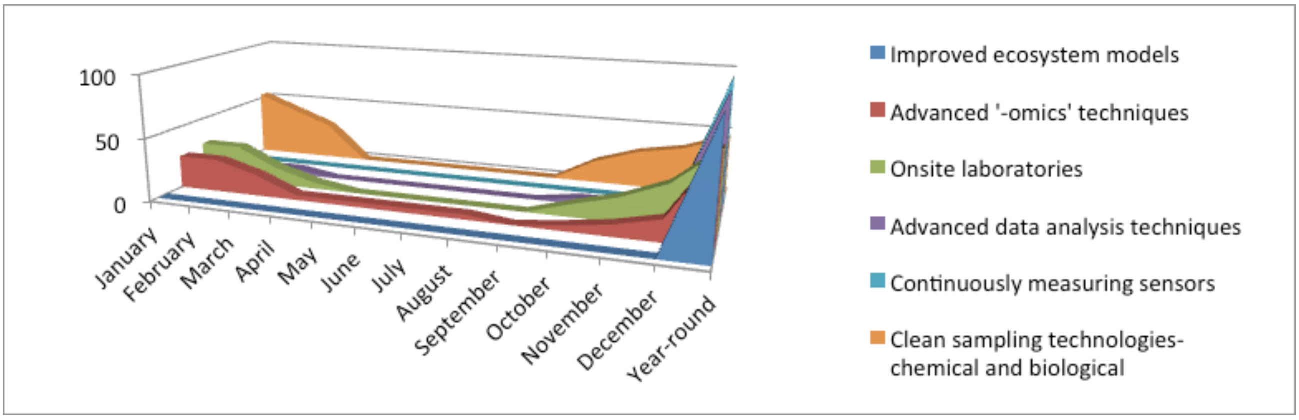
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top six)	Q: Does this technology currently exist?	Q: Is this technology available to you?
48% N=12	Remote solid Earth sensor arrays-seismic, magnetic, etc.	91% yes; 9% partly	80% yes; 20% no
30% N=8	Ice, sediment & rock down borehole loggers & sensors	75% yes; 13% no; 13% partly	33% yes; 67% no
30% N=8	Subglacial sampling technologies	60% yes; 40% no	33% yes; 67% no
26% N=7	Ice sheet/ice shelf drilling/core recovery technologies	100% yes	20% yes; 80% no
26% N= 7	Improved geological models	71% yes; 14% no; 14% partly	75% yes; 25% no
26% N=7	Oceanic sea bed drilling/core recovery technologies	100% yes	29% yes; 71% no

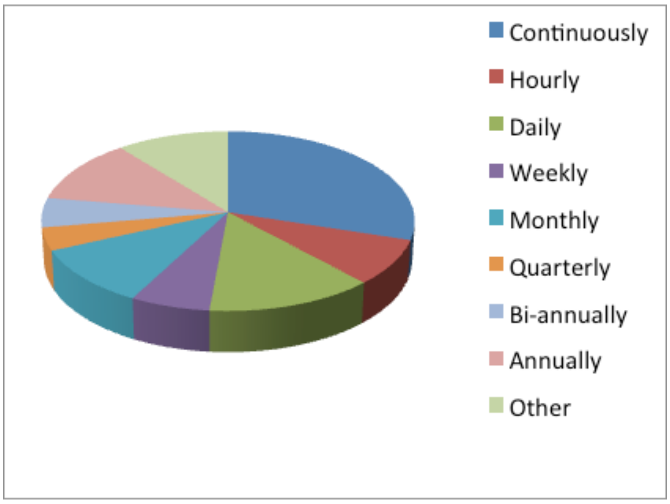
Q: In what setting would this technology be used?



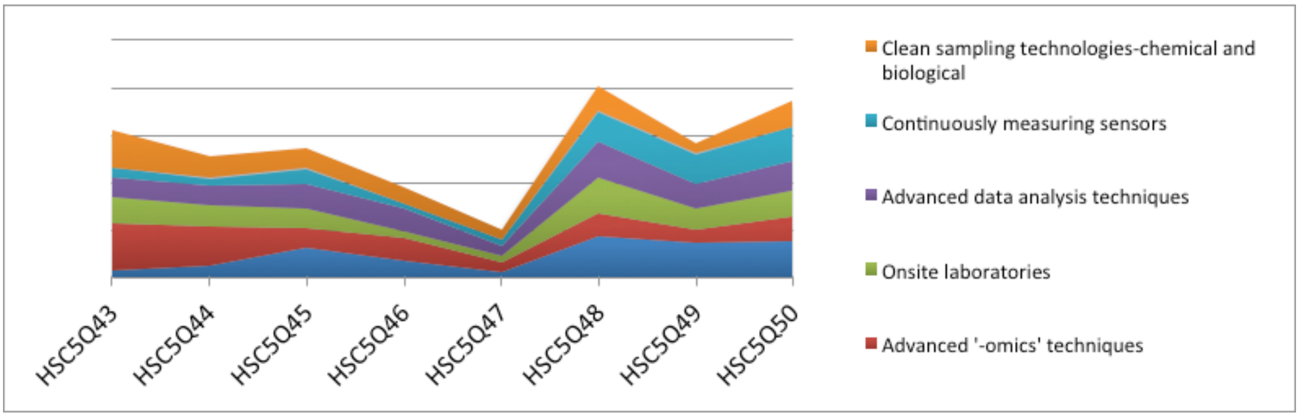
Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 4 questions does this technology specifically apply to?



Penguins in front of Dumont d'Urville Station

Photo: E. Amice, IPEV

HORIZON SCAN CLUSTER 5:

Antarctic Life on the Precipice

"Antarctic ecosystems were long thought of as young, simple, species-poor and isolated. In the past decade a different picture has emerged. Some taxa, such as marine worms (polychaetes) and crustaceans (isopods and amphipods) are highly diverse, and connections between species on the continent, neighboring islands and the deep sea are greater than thought. Molecular studies reveal that nematodes, mites, midges and freshwater crustaceans survived past glaciations. To forecast responses to environmental change we need to learn how past events have driven diversifications and extinctions. What are the genomic, molecular and cellular bases of adaptation? How do rates of evolution in the Antarctic compare with elsewhere? Are there irreversible environmental thresholds? And which species respond first?"
Kennicutt et al., 2014 *Nature* COMMENT

HSC5Q43: What is the genomic basis of adaptation in Antarctic and Southern Ocean organisms and communities?

HSC5Q44: How fast are mutation rates and how extensive is gene flow in the Antarctic and the Southern Ocean?

HSC5Q45: How have ecosystems in the Antarctic and the Southern Ocean responded to warmer climate conditions in the past?

HSC5Q46: How has life evolved in the Antarctic in response to dramatic events in the Earth's history?

HSC5Q47: How do subglacial systems inform models for the development of life on Earth and elsewhere?

HSC5Q48: Which ecosystems and food webs are most vulnerable in the Antarctic and Southern Ocean, and which organisms are most likely to go extinct?

HSC5Q49: How will threshold transitions vary over different spatial & temporal scales & how will they impact ecosystem functioning under future environmental conditions?

HSC5Q50: What are the synergistic effects of multiple stressors and environmental change drivers on Antarctic and Southern Ocean biota?

HSC5Q51: How will organism and ecosystems respond to a changing soundscape in the Southern Ocean?

HSC5Q52: How will next-generation contaminants affect Antarctic and Southern Ocean biota and ecosystems?

HSC5Q53: What is the exposure & response of Antarctic organisms & ecosystems to atmospheric contaminants-are sources & distributions of these contaminants changing?

HSC5Q54: How will the sources and mechanisms of dispersal of propagules into and around the Antarctic and Southern Ocean change in the future?

HSC5Q55: How will invasive species and range shifts of indigenous species change Antarctic and Southern Ocean ecosystems?

HSC5Q56: How will climate change affect the risk of spreading emerging infectious diseases in Antarctica?

HSC5Q57: How will increases in the ice-free Antarctic intertidal zone impact biodiversity and the likelihood of biological invasions?

HSC5Q58: How will climate change affect existing and future Southern Ocean fisheries, especially krill stocks?

HSC5Q59: How will linkages between marine and terrestrial systems change in the future?

HSC5Q60: What are the impacts of changing seasonality and transitional events on Antarctic and Southern Ocean marine ecology, biogeochemistry and energy flow?

HSC5Q61: How will increased marine resource harvesting impact Southern Ocean biogeochemical cycles?

HSC5Q62: How will deep sea ecosystems respond to modifications of deep water formation, and how will deep sea species interact with shallow water ecosystems as the environment changes?

HSC5Q63: How can changes in the form and frequency of extreme events be used to improve biological understanding and forecasting?

HSC5Q64: How can temporal and spatial 'omic-level' analyses of Antarctic and Southern Ocean biodiversity inform ecological forecasting?

HSC5Q65: What will key marine species tell us about trophic interactions and their oceanographic drivers such as future shifts in frontal dynamics and stratification?

HSC5Q66: How successful will Southern Ocean MPAs be in meeting their protection objectives, and how will they affect ecosystem processes and resource extraction?

HSC5Q67: What ex situ conservation measures, such as genetic repositories, are required for the Antarctic and Southern Ocean?

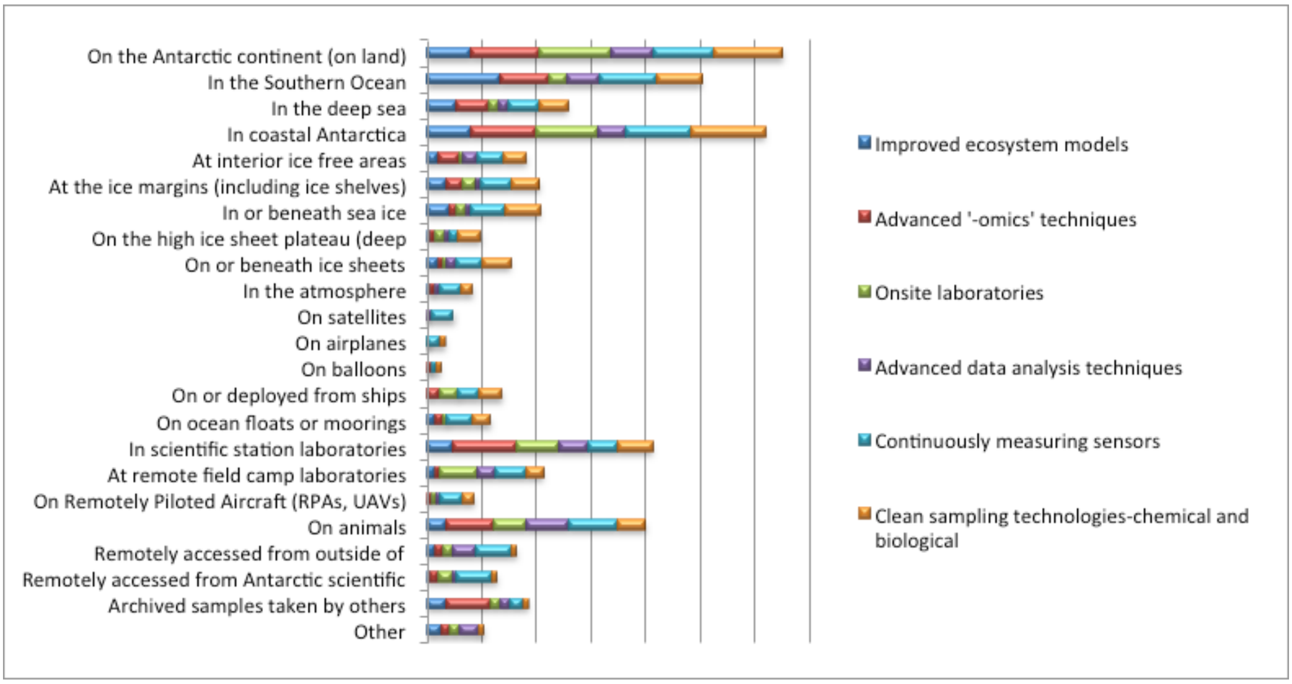
HSC5Q68: How effective are Antarctic and Southern Ocean conservation measures for preserving evolutionary potential?

Antarctic Roadmap Challenges Survey 1:

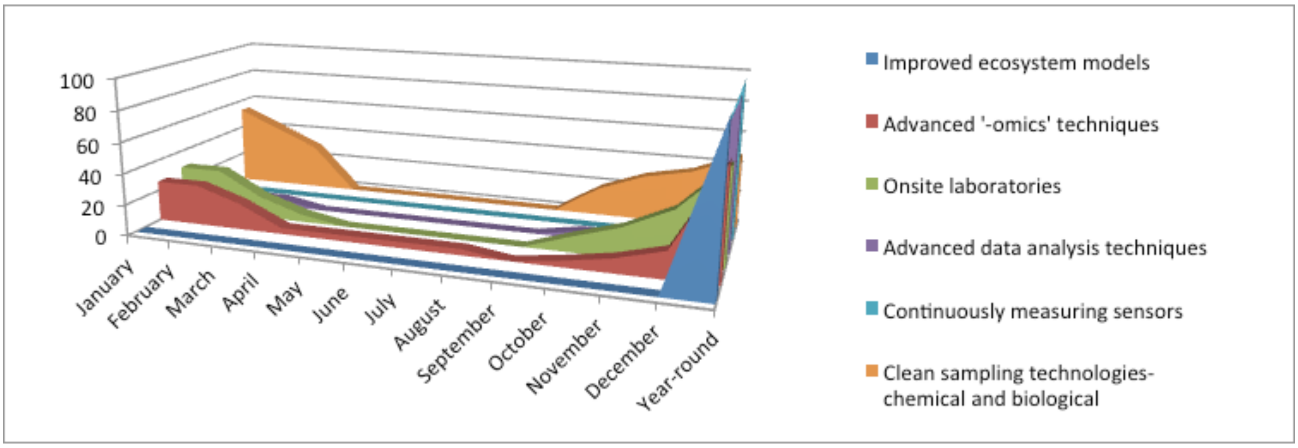
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top six)	Q: Does this technology currently exist?	Q: Is this technology available to you?
43% N=34	Improved ecosystem models	38% yes; 38% no; 25% partly	50% yes; 50% no
40% N=33	Advanced '-omics' techniques	96% yes; 4% no	57% yes; 39% no; 4% partly
35% N=29	Onsite laboratories	70% yes; 13% no; 17% partly	50% yes; 50% no
35% N=29	Advanced data analysis techniques	74% yes; 11% no; 10% partly	62% yes; 38% no
31% N=26	Continuously measuring sensors	86% yes; 14% partly	33% yes; 56% no; 11% partly
30% N=25	Clean sampling technologies-chemical and biological	88% yes; 14% no	31% yes; 62% no; 8% partly

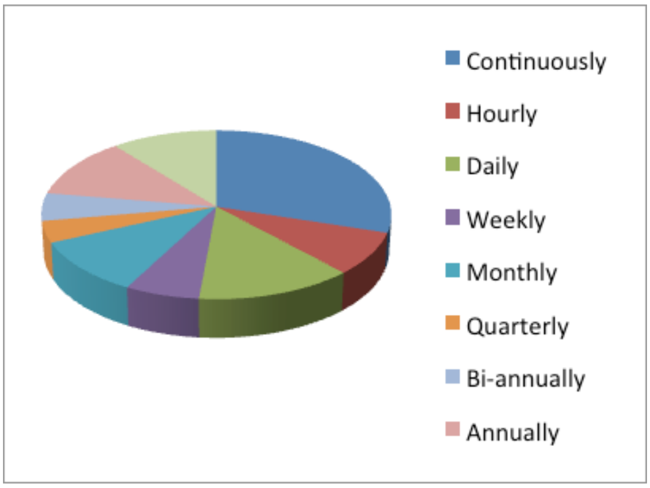
Q: In what setting would this technology be used?



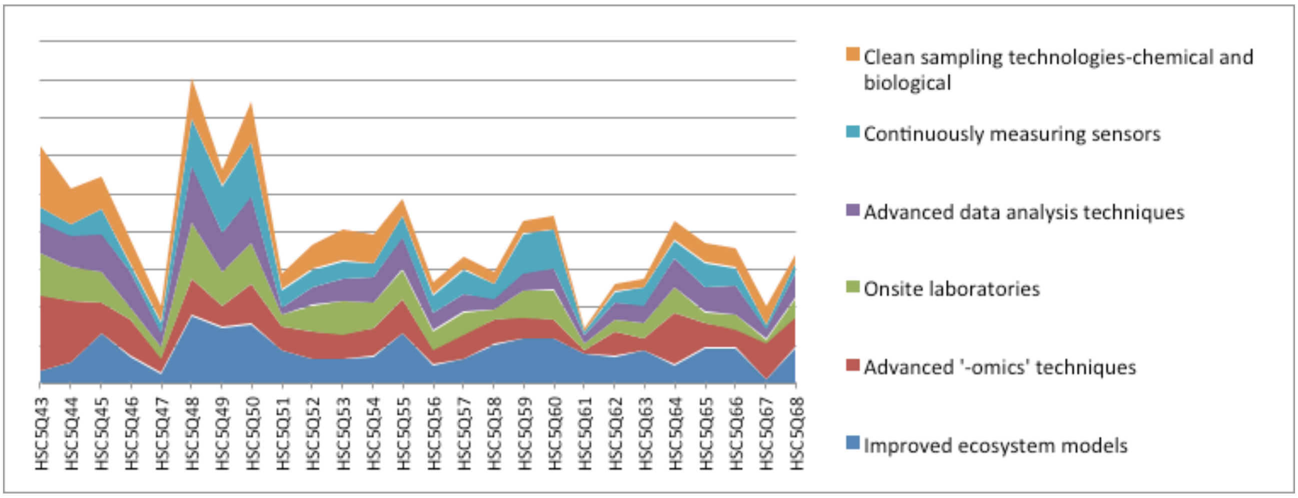
Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 5 questions does this technology specifically apply to?



The Dark Sector Lab at Amundsen-Scott South Pole Station is home to the South Pole Telescope, left, and BICEP-3 experiments. Both telescopes are using the leftover glow from the Big Bang, called the cosmic microwave background, to study the early evolution of the universe.

Photo: M. Lucibella, US National Science Foundation

HORIZON SCAN CLUSTER 6:

Near Earth space and beyond – eyes on the sky

"The dry, cold and stable Antarctic atmosphere creates some of the best conditions on Earth for observing space. Lakes beneath Antarctic glaciers mimic conditions on Jupiter and Saturn's icy moons, and meteorites collected on the continent reveal how the Solar System formed and inform astrobiology. We have limited understanding of high-energy particles from solar flares that are funneled to the poles along the Earth's magnetic field lines. What is the risk of solar events disrupting global communications and power systems? Can we prepare for them and are they predictable?"
Kennicutt et al., 2014 *Nature* COMMENT

HSC6Q69: What happened in the first second after the universe began?

HSC6Q70: What is the nature of the Dark Universe and how is it affecting us?

HSC6Q71: What are the differences in the inter-hemispheric conjugacy between the ionosphere and that in the lower, middle and upper atmospheres, and what causes those differences?

HSC6Q72: How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere?

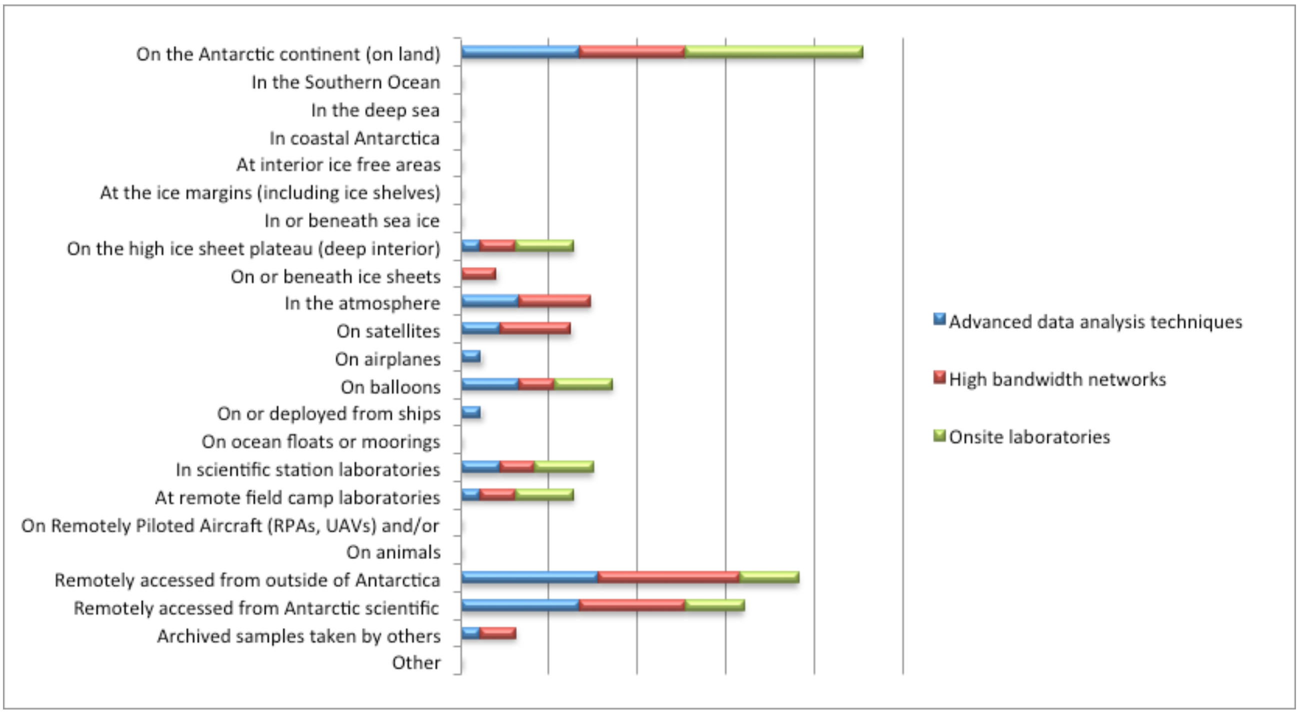
HSC6Q73: How do the generation, propagation, variability and climatology of atmospheric waves affect atmospheric processes over Antarctic and the Southern Ocean?

Antarctic Roadmap Challenges Survey 1:

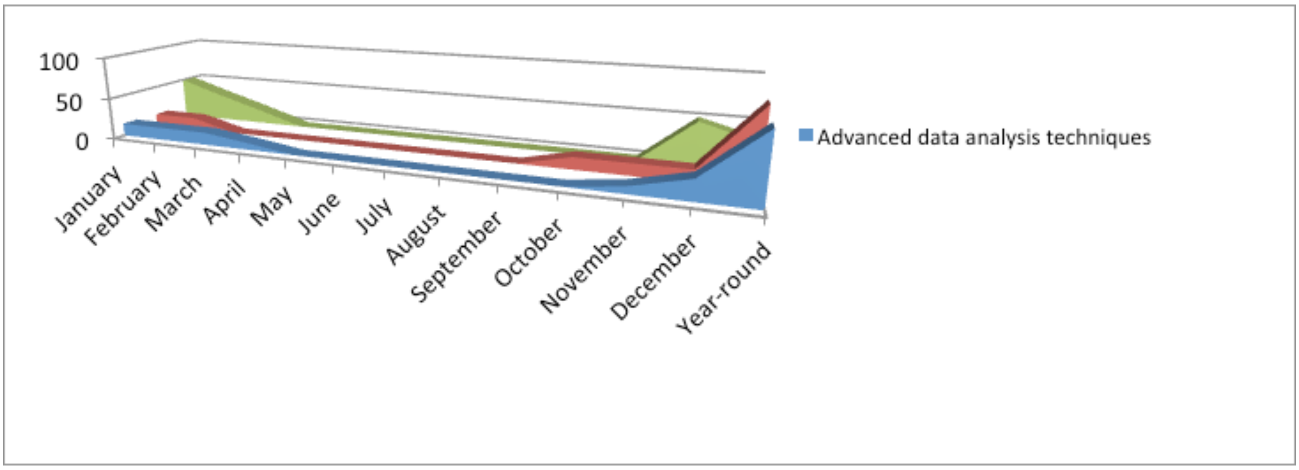
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top three)	Q: Does this technology currently exist?	Q: Is this technology available to you?
82% N=9	Advanced data analysis techniques	87% yes; 13% no	50% yes; 50% no
55% N=6	High bandwidth networks	80% yes; 20% no	100% no
36% N=4	Onsite laboratories	100% yes	67% yes; 33% no

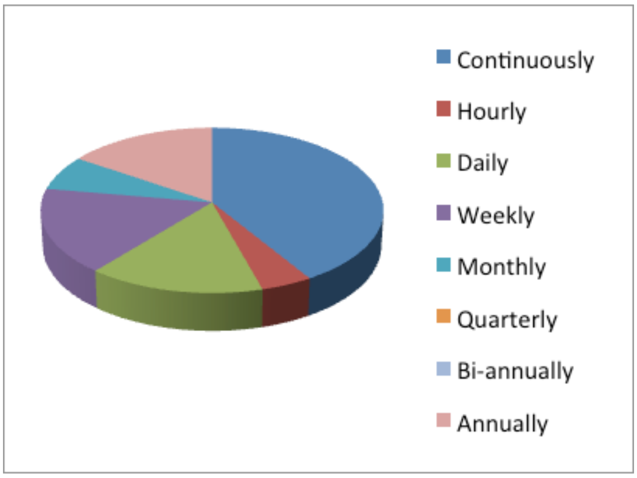
Q: In what setting would this technology be used?



Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 6 questions does this technology specifically apply to?

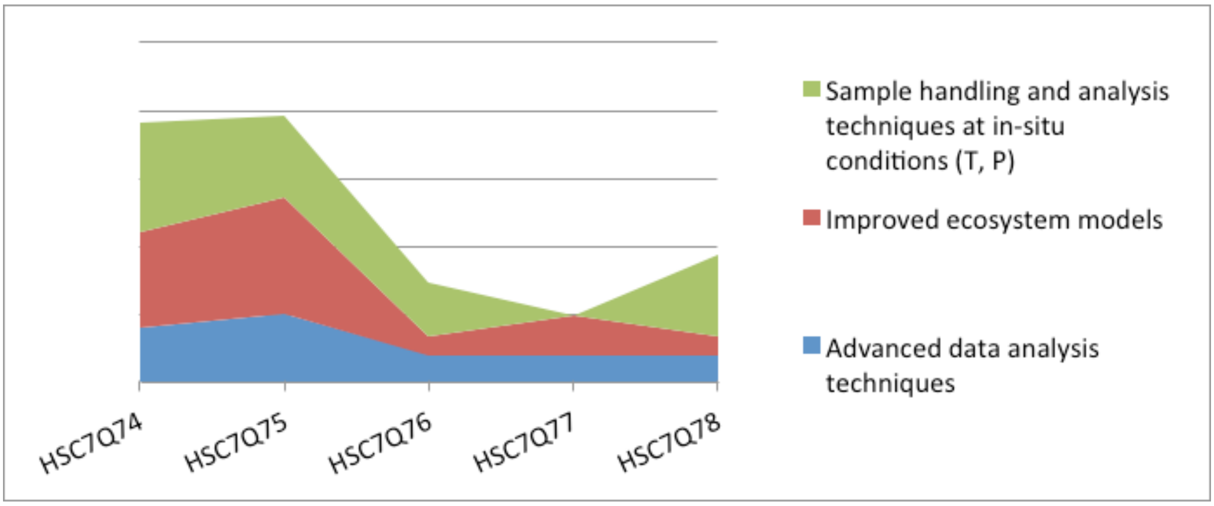


Photo: CCAMLR Secretariat

fishing for Antarctic krill (*Euphausia superba*) which is regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)

HORIZON SCAN CLUSTER 7:

Human presence in Antarctica

"Forecasts of human activities and their impacts on the region are required for effective Antarctic governance and regulation. Natural and human impacts must be disentangled. How effective are current regulations in controlling access? How do global policies affect people's motivations to visit the region? How will humans and pathogens affect and adapt to Antarctic environments? What is the current and potential value of Antarctic ecosystem services and how can they be preserved?"
Kennicutt et al., 2014 *Nature* COMMENT

HSC7Q74: How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance?

HSC7Q75: What will be the impacts of large-scale, direct human modification of the Antarctic environment?

HSC7Q76: How will external pressures and changes in the geopolitical configurations of power affect Antarctic governance and science?

HSC7Q77: How will the use of Antarctica for peaceful purposes and science be maintained as barriers to access change?

HSC7Q78: How will regulatory mechanisms evolve to keep pace with Antarctic tourism?

HSC7Q79: What is the current and potential value of Antarctic ecosystem services?

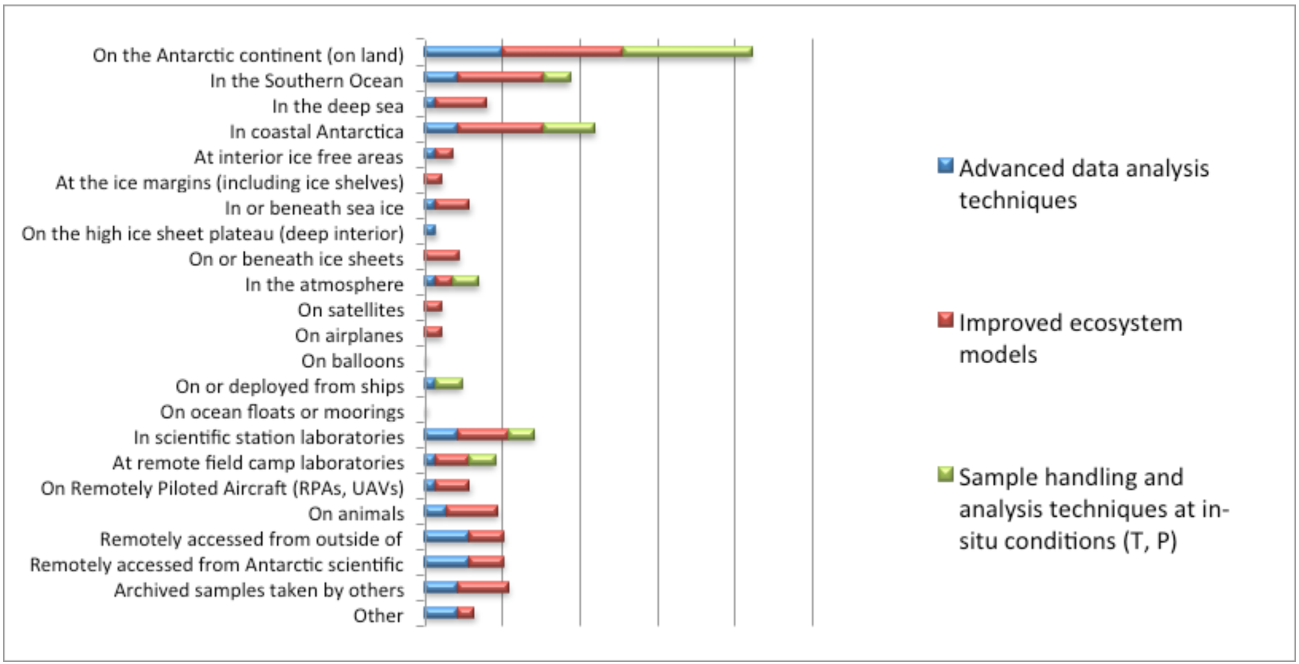
HSC7Q80: How will humans, diseases and pathogens change, impact and adapt to the extreme Antarctic environment?

Antarctic Roadmap Challenges Survey 1:

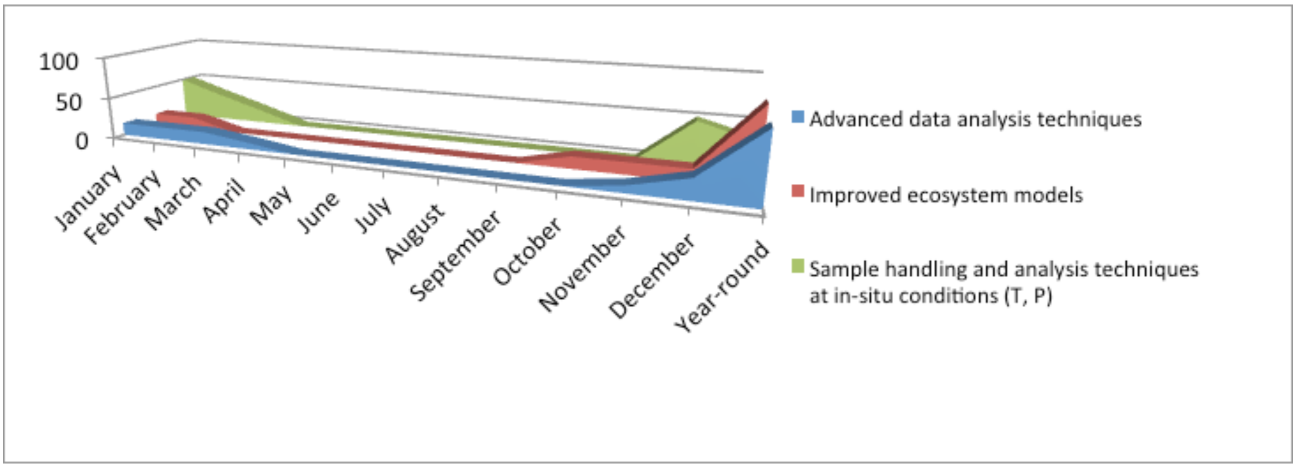
Q: With no constraints, what specific technologies (not timing or access) do you require to do the research necessary to answer the questions in this cluster?

	(top six)	Q: Does this technology currently exist?	Q: Is this technology available to you?
44% N=16	Advanced data analysis techniques	58% yes; 33% no; 8% partly	29% yes; 57% no; 14% partly
31% N=11	Improved ecosystem models	38% yes; 38% no; 25% partly	67% yes; 33% partly
23% N=9	Sample handling and analysis techniques at in-situ conditions (T, P)	100% yes	80% yes; 20% no

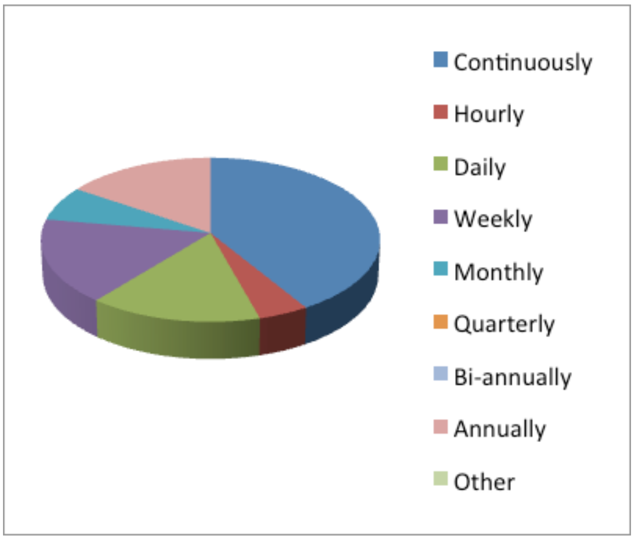
Q: In what setting would this technology be used?



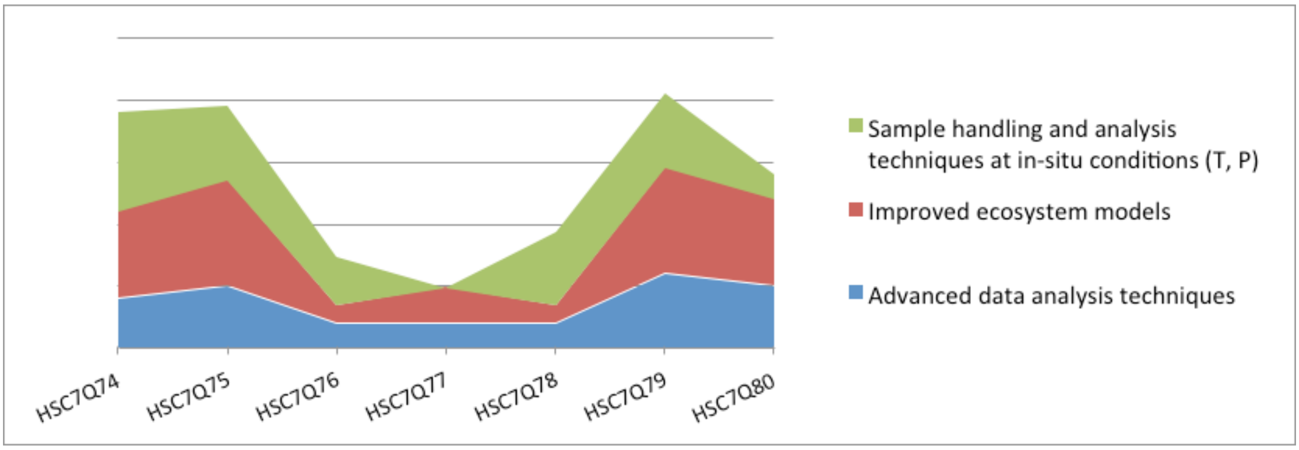
Q: In which months of the year would this technology be used?



Q: In the case of measurement technologies, what is the temporal frequency of data collection?



Q: Which Cluster 7 questions does this technology specifically apply to?



Meteorological observations at Mizuho Station – preparations of equipment, JARE12

Photo: NIPR

SECTION 3: Logistics, Infrastructure and Access Requirements

Q: Choose up to five of the listed critical logistics, infrastructure and access requirements you consider the most important in delivering your future Antarctic research.

The List (as it appeared in the survey, alphabetically)	Number of times chosen	Overall ranking* (1=most important)
Access to coastal regions	86	1.69
Access to the deep ocean for sampling and emplacement of observatories	25	2.36
Access to the interior of Antarctica	70	2.13
Airborne sensors	27	2.93
An inter-hemispheric near-Earth space monitoring network	7	3.29
Benthic and pelagic oceanic sampling gear	29	2.48
Deep field camps	39	2.87
Deep sea manned and unmanned submersibles	18	2.89
Deep-sea towed video and sensor arrays	5	2.80
Deployment of ultra-long duration balloons	8	2.63
Expanded telescope and astrophysics sensor arrays	8	2.88
High-plateau research station	23	2.65
Increased icebreaker availability	51	2.71
Increased ship availability	48	2.48
Networks of buoys in the ocean	18	2.89
Network of stations continuously conducting atmospheric monitoring in both polar regions	35	2.80
Network of stations continuously conducting wave energy monitoring	8	2.75
Network of stations continuously conducting under-ice monitoring	15	3.27
Onsite laboratories for sample processing	46	3.09
Open-access databases	55	2.98
Remote placement of instrument arrays	30	2.80
Shelf- to deep-sea monitoring station	15	3.56
"Supersites" where suites of observing tools (ocean, surface, air) create a common 'natural laboratory'	31	3.55
Trans-continental access	7	3.14
Traverse capabilities	26	3.00
Under-ice sheet monitoring and observing	17	3.47
Under-ice shelf monitoring and observing	25	3.04
Under-sea ice monitoring and observing	25	3.08
"Wet" storage (long term storage of genomic materials under cool temperatures)	19	3.47
Year-round access to the continent	30	3.47
Year-round access to the Southern Ocean	34	3.32
Other (Access) [free text]: Geographic information, Antarctic stations & personnel, Year-round sea ice, Data networks, Easier permitting, Historical sites, Remote sensing, Open meetings, Operations information sharing, remote rock outcrops, Humanities support, Tourist sites.		
Other (Infrastructure) [free text]: Communication networks, Animal borne sensors, CTDO instrumentation for water collection, Surface snow observations, Telemedicine capabilities, Increased ship-based helicopters, Fishing, Aquaria, Multibeam, Integrated cryosphere observing sites, Ocean gliders & floats, Sub-ice geological drilling, Inter-continental biological sample transport.		

* Note: once chosen, the five choices could be ranked from 1 (most important) to 5.

Appendix 2: ARC SURVEY 2

ARC Survey 2 used the specific technology results from Survey 1. It pooled all the specific technology results from all seven Horizon Scan clusters together; so, this survey was not structured around each of the clusters as in the first survey.

ARC Survey 2 was intended to assist in determining the feasibility of technological and operational requirements within the context of currently planned investments over the next two decades. It was structured into three sections: Demographics, Prioritized Technology Requirements and Access, Infrastructure and Logistics Requirements. The Prioritized Technology Requirements section was further broken down into three subsections: Development Status, Financial Implications and International Collaboration. The Access, Infrastructure and Logistics Requirements section was further broken down into three subsections: Planning Status, International Collaboration and Financial Implications.

Opened on-line on 9 July 2015; Closed 17 August 2015; Powered by Qualtrics software.

257 people begun the survey; 108 of those completed the survey in full; 149 completed a portion of the survey; All responses are considered even in the case that the survey was not entirely completed.

SECTION 1: The Demographics of Respondents

Gender: 33% female, 65% male and 2% chose not to respond

Country of residence for majority of year:

16%	New Zealand	14%	Australia	12%	United States
8%	United Kingdom	6%	Japan	4%	Germany
3%	Spain	3%	France	3%	Republic of Korea
3%	Belgium	3%	China	2%	Norway
2%	South Africa	2%	Ecuador	2%	Argentina
2%	Chile	2%	Italy	1%	India
1%	Canada	1%	Switzerland	1%	Russia
<1% each	Afghanistan, Brazil, Czech Republic, Dominican Republic, Greece, Malaysia, Mauritius Portugal, Sweden				

In what capacity are you responding to this survey?

58%	Scientist/Researcher	**6%**	National Antarctic Program Manager	**6%**	Other
Those **58%** were asked two additional questions:		**4%**	National Antarctic Program Support Person	**5%** each	Interested Citizen, Graduate Student
1) Which of the SCAR groups most closely align with your interests?		**2%** each	Engineer, Logistician	**3%** each	Educator, Postdoctoral Appointee
43%	Geosciences	**1%** each	Technician, Medical Doctor	**2%**	Policy maker
28%	Physical Sciences	Those **16%** were asked one additional question:			
23%	Life Sciences	**1) Are you a member of any of the COMNAP Expert Groups?**			
6%	Social Sciences/ Humanities	46%	No		
2) Select the discipline or topic which most closely aligns with your area of research:		29%	Safety		
9%	Sea Ice	17%	Shipping		
8% each	Geology, Cryosphere, Biological Oceanography	13% each	Air, Environment		
7% each	Physical Oceanography, Ecology	8% each	Training, Science		
6% each	Atmospheric Science, Geophysics	4% each	Energy & Technology, Medical		
5%	Biology				
3% each	Paleoclimate, Glaciology, Ice Core Science, Geological Oceanography, Climate Science, Astronomy & Astrophysics, Birds & Marine Mammals				
2% each	Biodiversity, History, Remote Sensing, Chemistry, Human Biology & Medicine				
1% each	Numeric Modeling, Near-Earth Space Science, Ocean Observing, Conservation, Policy, Meteorology, Arts, Law/Governance, Humanities, Climatology, Chemical Oceanography				

Scientist at work, Arctowski Station

Photo: Latuesk, PAS

SECTION 2:
Prioritized Technology Requirements
Subsection: Development Status

Q: The following technologies were identified by the Antarctic research community in ARC Survey 1 as the highest priority. Please indicate the status of the technologies you are familiar with and click “Don’t Know” for those technologies which you are uncertain.

The List (as it appeared in the survey, alphabetically)

Advanced data analysis techniques
Advanced ‘-omics’ techniques
Below ice sheet observing systems and the associated power and sensors requirements
Calibration/validation of available satellite sensors
Clean sampling technologies – chemical and biological
Continuous measuring sensors
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities
High bandwidth networks
Ice, sediment, and rock down boreholes loggers and sensors
Ice sheet/ice shelf drilling/core recovery technologies
Ice sheet and shelf observatories
Improved climate models
Improved ecosystem models
Improved geological models
Improved glaciological models
Integrated Earth System models
Oceanic sea bed drilling/core recovery technologies
On-site laboratories
Remotely Operated Underwater Vehicles (ROVs) and/or Unpersoned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads
Remote solid Earth sensor arrays –seismic, magnetic, etc.
Remote weather stations with expanded and robust sensor arrays
Sample handling and analysis techniques at in situ conditions (T,P)
Subglacial sampling technology

The “status” choices were:

- Such technology development is beyond “Antarctic” organisations
- Developed and available
- Not currently under development
- Currently under development
- Don’t know

Such technology is beyond "Antarctic" organisations

	Times selected	Total responses	Percentage
Advanced '-omics' techniques	6	51	12%
Improved ecosystem models	7	90	8%
Oceanic sea bed drilling/core recovery technologies	7	88	8%
High bandwidth networks	7	86	8%
Improved climate models	9	126	7%
Advanced data analysis techniques	9	126	7%
Integrated Earth System models	7	104	7%
Calibration/validation of available satellite sensors	7	101	7%
Improved geological models	5	76	7%
Ice, sediment, and rock down boreholes loggers and sensors	5	96	5%
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	4	89	4%
Continuous measuring sensors	2	125	2%
Ice sheet/ice shelf drilling/core recovery technologies	2	99	2%
Improved glaciological models	2	98	2%
Below ice sheet observing systems and the associated power and sensors requirements	2	96	2%
Clean sampling technologies – chemical and biological	2	94	2%
Ice sheet and shelf observatories	2	89	2%
Remote weather stations with expanded and robust sensor arrays	1	107	1%
Subglacial sampling technology	1	81	1%
Remote solid Earth sensor arrays –seismic, magnetic, etc.	1	72	1%
On-site laboratories	0	112	0%
Remotely Operated Underwater Vehicles (ROVs) and/or Unpersoned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads	0	108	0%
Sample handling and analysis techniques at in situ conditions (T,P)	0	76	0%

Developed and available

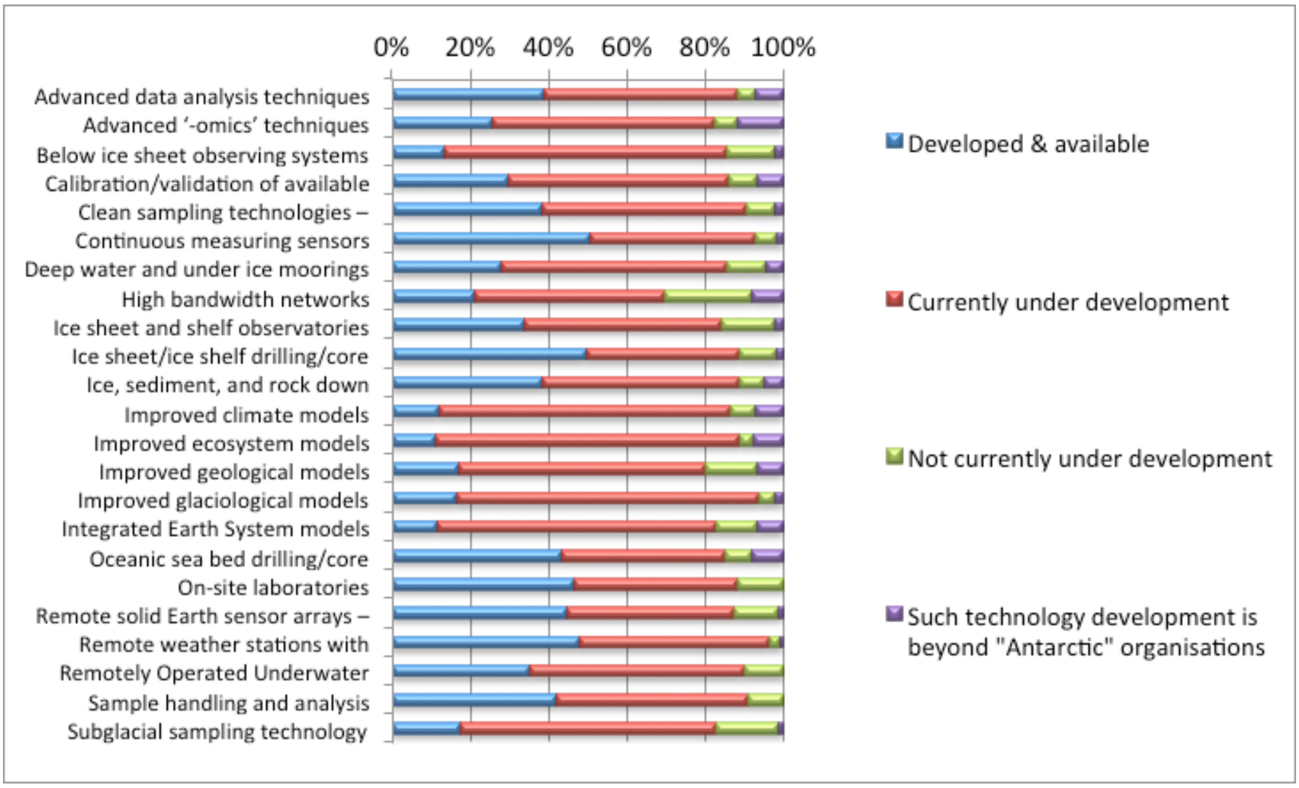
	Times selected	Total responses	Percentage
Continuous measuring sensors	63	125	50%
Ice sheet/ice shelf drilling/core recovery technologies	49	99	49%
Remote weather stations with expanded and robust sensor arrays	51	107	48%
On-site laboratories	52	112	46%
Remote solid Earth sensor arrays –seismic, magnetic, etc.	32	72	44%
Oceanic sea bed drilling/core recovery technologies	38	88	43%
Sample handling and analysis techniques at in situ conditions (T,P)	32	76	42%
Advanced data analysis techniques	49	126	39%
Ice, sediment, and rock down boreholes loggers and sensors	37	96	39%
Clean sampling technologies – chemical and biological	36	94	38%
Remotely Operated Underwater Vehicles (ROVs) and/or Unpersoned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads	38	108	35%
Ice sheet and shelf observatories	30	89	34%
Calibration/validation of available satellite sensors	30	101	30%
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	25	89	28%
Advanced '-omics' techniques	13	51	25%
High bandwidth networks	18	86	21%
Subglacial sampling technology	14	81	17%
Improved geological models	13	76	17%
Improved glaciological models	16	98	16%
Below ice sheet observing systems and the associated power and sensors requirements	13	96	14%
Improved climate models	15	126	12%
Integrated Earth System models	12	104	12%
Improved ecosystem models	10	90	11%

Not currently under development	Times selected	Total responses	Percentage
High bandwidth networks	19	86	22%
Subglacial sampling technology	13	81	16%
Below ice sheet observing systems and the associated power and sensors requirements	12	96	13%
Ice sheet and shelf observatories	12	89	13%
Improved geological models	10	76	13%
On-site laboratories	13	112	12%
Integrated Earth System models	11	104	11%
Remotely Operated Underwater Vehicles (ROVs) and/or Unpersoned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads	11	108	10%
Remote solid Earth sensor arrays –seismic, magnetic, etc.	8	72	11%
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	9	89	10%
Ice sheet/ice shelf drilling/core recovery technologies	9	99	9%
Sample handling and analysis techniques at in situ conditions (T,P)	7	76	9%
Calibration/validation of available satellite sensors	7	101	7%
Clean sampling technologies – chemical and biological	7	94	7%
Oceanic sea bed drilling/core recovery technologies	6	88	7%
Improved climate models	8	126	6%
Continuous measuring sensors	7	125	6%
Ice, sediment, and rock down boreholes loggers and sensors	6	96	6%
Advanced '-omics' techniques	3	51	6%
Advanced data analysis techniques	6	126	5%
Improved glaciological models	4	98	4%
Remote weather stations with expanded and robust sensor arrays	3	107	3%
Improved ecosystem models	3	90	3%

Currently under development	Times selected	Total responses	Percentage	Near future (within 2 years)	Future (within 3-9 years)	Far future (10years or more)
Improved glaciological models	76	98	78%	80%	20%	0%
Improved ecosystem models	70	90	78%	14%	67%	19%
Improved climate models	94	126	75%	19%	71%	
Below ice sheet observing systems and the associated power and sensors requirements	69	96	72%	10%	72%	10%
Integrated Earth System models	74	104	71%	10%	56%	18%
Subglacial sampling technology	53	81	65%	29%	52%	34%
Improved geological models	48	76	63%	25%	56%	19%
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	51	89	57%	32%	53%	19%
Advanced '-omics' techniques	29	51	57%	43%	48%	15%
Calibration/validation of available satellite sensors	57	101	56%	44%	52%	9%
Remotely Operated Underwater Vehicles (ROVs) and/or Unpersoned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads	59	108	55%	36%	55%	10%
Clean sampling technologies – chemical and biological	49	94	52%	38%	58%	5%
Ice sheet and shelf observatories	45	89	51%	31%	58%	11%
Ice, sediment, and rock down boreholes loggers and sensors	48	96	50%	50%	47%	3%
Advanced data analysis techniques	62	126	49%	44%	54%	1%
High bandwidth networks	42	86	49%	34%	58%	8%
Sample handling and analysis techniques at in situ conditions (T,P)	37	76	49%	39%	46%	14%
Remote weather stations with expanded and robust sensor arrays	52	107	49%	51%	45%	4%
Remote solid Earth sensor arrays –seismic, magnetic, etc.	31	72	43%	35%	58%	6%
Continuous measuring sensors	53	125	42%	70%	27%	3%
Oceanic sea bed drilling/core recovery technologies	37	88	42%	42%	53%	5%
On-site laboratories	47	112	42%	45%	43%	12%
Ice sheet/ice shelf drilling/core recovery technologies	39	99	39%	43%	49%	8%

Graphic summary of Development Status results

In the graph below, those technologies with the greatest total amount of blue and red are those that are developed and available or are currently under development. Those technologies with the greatest amount of green and purple indicate technology that is required that is not currently under development and what national Antarctic programs cannot be expected to develop alone, that is, a technology that is “beyond Antarctic organisations” but is needed. Such technology development will require communications with the external community.



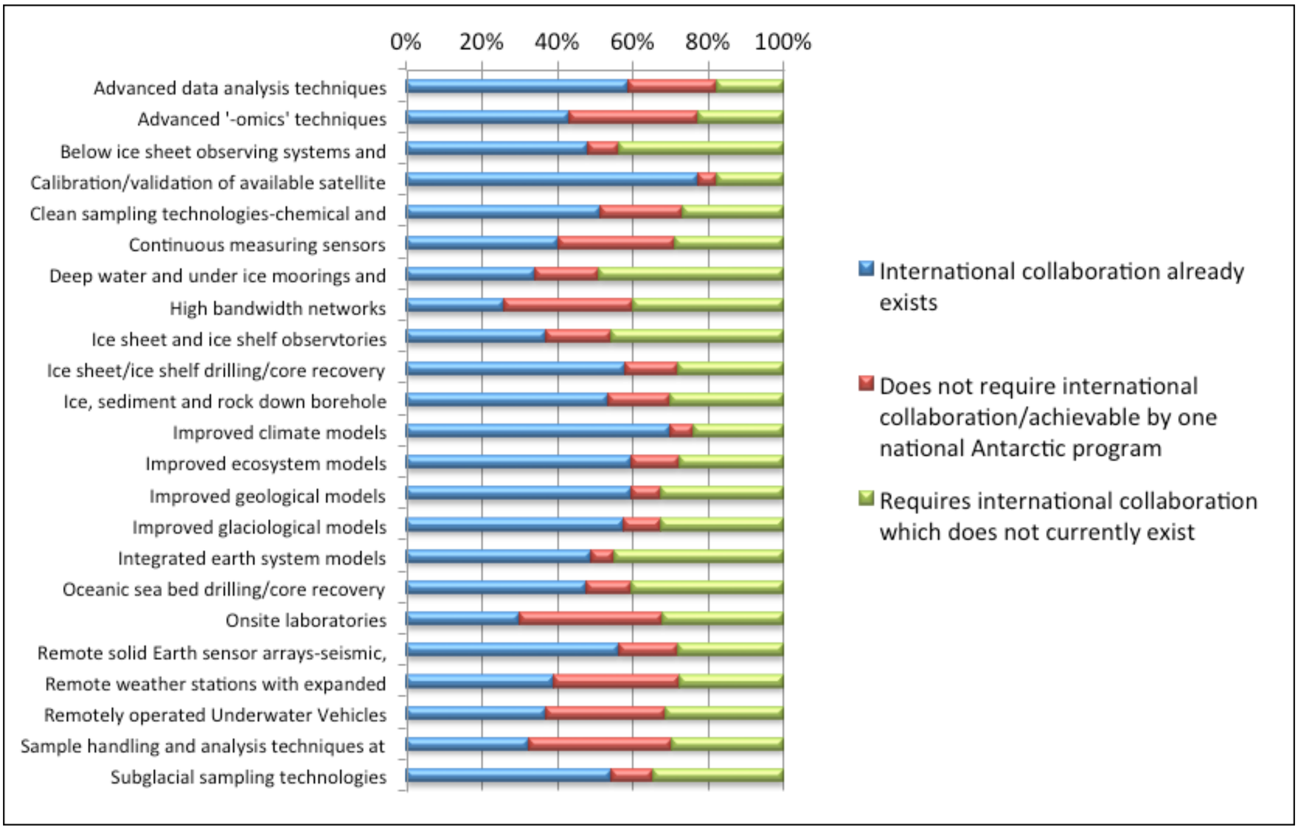
SECTION 2:
Prioritized Technology Requirements
Subsection: Financial Implications

Q: To better define the feasibility of these high priority technological requirements, please indicate your assessment of the cost to deliver/ develop these technologies. This is not intended to be a rigorous cost analysis, but a general indication of the cost range to the best of your estimation.
Select “Don’t know” if you have no basis for such an estimate.

Listed from most costly (at top) to least costly (at bottom)	to $10,000 USD	$10,000 to $100,000 USD	$100,000 to $500,000 USD	$500,000 to $1,000,000 USD	$1,000,000 to $10,000,000 USD	More than $10,000,000 USD	Total Responses	Don’t know
High bandwidth networks	1%	3%	7%	6%	8%	9%	110	72
Oceanic sea bed drilling/core recovery technologies	1%	1%	3%	5%	17%	12%	107	66
Ice sheet/ice shelf drilling/core recovery technologies	0%	2%	3%	6%	19%	13%	108	62
Ice sheet and ice shelf observatories	0%	3%	4%	6%	20%	11%	107	61
Remotely Operated Underwater Vehicles and/or Unpersonned Autonomous Underwater Vehicles (UAVs) with expanded sensor payloads	1%	4%	8%	6%	28%	4%	108	53
Integrated Earth system models	1%	5%	2%	5%	20%	7%	108	65
On-site laboratories	4%	3%	10%	11%	18%	9%	109	49
Below ice sheet observing systems and the associated power and sensors requirements	0%	2%	7%	13%	16%	3%	116	68
Improved climate models	2%	7%	5%	8%	16%	9%	107	57
Subglacial sampling technologies	0%	0%	4%	6%	16%	8%	108	72
Calibration/validation of available satellite sensors	2%	8%	7%	7%	15%	4%	112	63
Deep water and under ice moorings and floats with tethered and/or wireless data transfer capabilities	1%	3%	2%	11%	14%	8%	108	66
Ice, sediment and rock down borehole loggers and sensors	1%	6%	5%	15%	14%	2%	108	62
Remote weather stations with expanded and robust sensors arrays	1%	6%	12%	14%	13%	1%	108	57
Remote solid Earth sensor arrays – seismic, magnetic, etc.	0%	3%	5%	5%	12%	4%	107	77
Improved ecosystem models	2%	8%	6%	8%	12%	2%	108	67
Improved glaciological models	2%	6%	6%	8%	12%	2%	108	68
Continuous measuring sensors	1%	9%	14%	15%	10%	0%	110	57
Clean sampling technologies – chemical and biological	0%	6%	15%	11%	9%	1%	110	64
Improved geological models	2%	7%	6%	7%	7%	2%	108	73
Sampling handling and analysis techniques at in-situ conditions (T, P)	2%	7%	12%	7%	7%	0%	107	71
Advanced ‘-omics’ techniques	3%	5%	5%	2%	5%	0%	118	94
Advanced data analysis techniques	6%	11%	13%	12%	4%	1%	120	64

SECTION 2:
Prioritized Technology Requirements
Subsection: International Collaboration

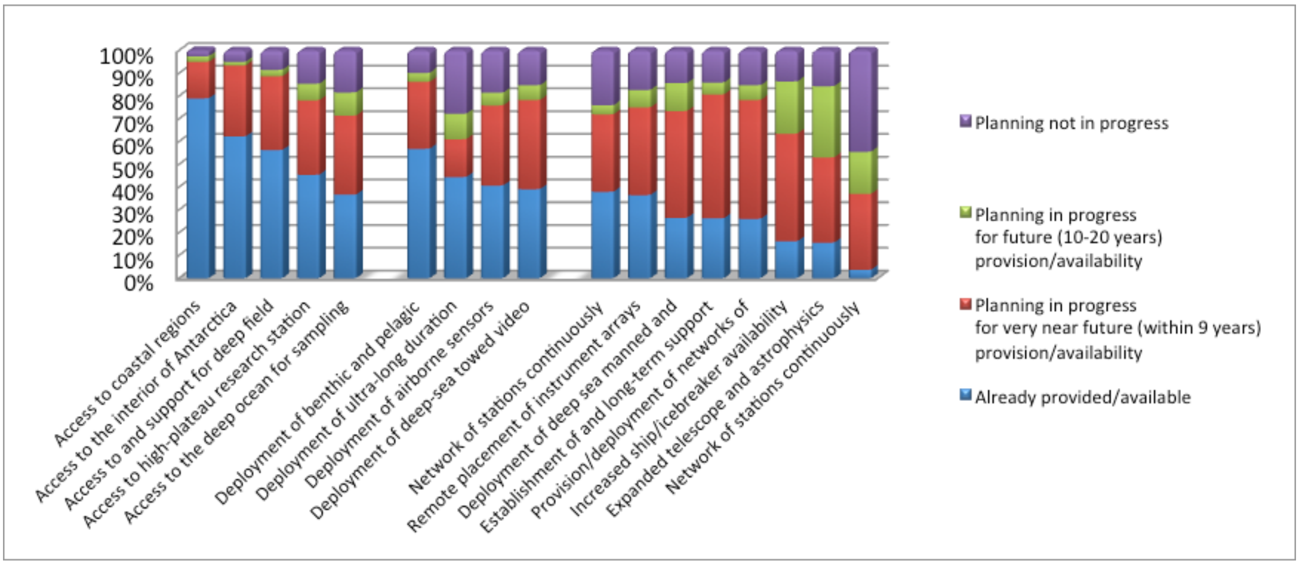
Q: Which of these technological developments are not achievable by one national Antarctic program acting alone? Assess only those technologies that you have personal knowledge of the requirements for development and do not guess at an answer.



In the graph above, those technologies with the greatest amount of green are those that require international collaboration which does not currently exist.

SECTION 3:
Access, Infrastructure and Logistics Requirements
Subsection: Planning Status

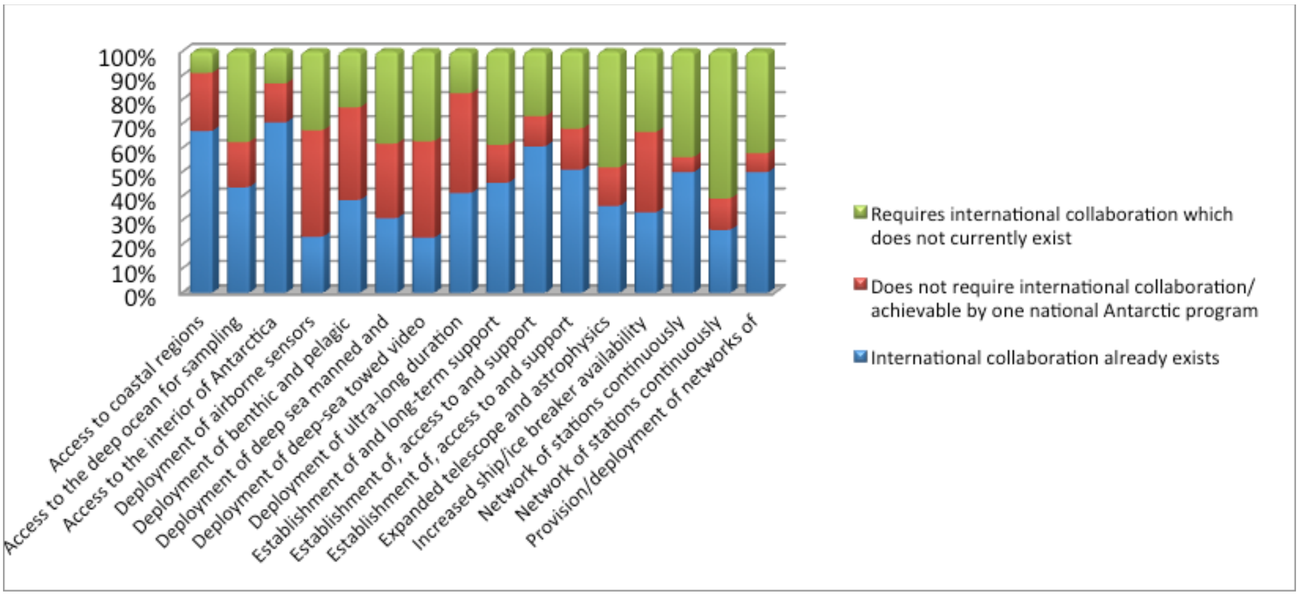
Q: The following list of access, infrastructure and logistics requirements were identified by the Antarctic research community in ARC Survey 1 to be of the highest priority to deliver future Antarctic research. Indicate the status of the requirements you are familiar with, leave any you are unsure about blank.



In the graph above, most of the access requirements are already provided or are in the planning stage. The logistical and infrastructure requirements with the greatest amount of purple are those that are not currently provided and do not have planning in progress.

SECTION 3:
Access, Infrastructure and Logistics Requirements
Subsection: International Collaboration

Q: Which of the access, infrastructure and logistics requirements are not achievable by one national Antarctic program acting alone? Assess only those that you have personal knowledge of the requirements for and just leave blank any that you are unsure of/make no selection for that requirement.



In the graph above, the access, infrastructure and logistics requirements with the greatest amount of green are those that require international collaboration which does not currently exist.

SECTION 3:
Access, Infrastructure and Logistics
Subsection: Financial Implications

Q: To better define the feasibility of these high priority access, infrastructure and logistical requirements, please indicate your assessment of the cost to deliver these requirements. This is not intended to be a rigorous cost analysis, but a general indication of the cost range to the best of your estimation. Select "Don't know" if you have no basis for such an estimate.

Listed from most costly (at top) to least costly (at bottom)	Up to $100,000 USD	$100,000 to $500,000 USD	$500,000 to $1,000,000 USD	$1,000,000 to $10,000,000 USD	More than $10,000,000 USD	Total Responses	Don't know
Increased ship/ice breaker availability	0%	1%	1%	4%	65%	77	22
Establishment of, access to and support for high-plateau research station	0%	0%	7%	14%	18%	74	46
Expanded telescope and astrophysics sensor arrays	0%	1%	1%	7%	16%	73	54
Network of stations continuously conducting wave energy monitoring	0%	1%	4%	3%	11%	72	58
Access to interior of Antarctica	2%	7%	5%	35%	4%	81	38
Deployment of deep-sea towed video and sensor arrays	0%	4%	11%	22%	3%	72	43
Establishment of, access to and support for deep field camps	1%	10%	10%	22%	3%	77	41
Deployment of airborne sensors	5%	8%	12%	21%	1%	75	41
Provision and deployment of networks of buoys in the ocean	0%	3%	8%	21%	12%	75	42
Deployment of deep-sea manned and unmanned submersibles	0%	1%	8%	21%	14%	72	40
Network of stations continuously conducting atmospheric monitoring in both polar regions	0%	5%	5%	20%	17%	75	39
Access to coastal regions	14%	16%	8%	19%	8%	80	29
Access to deep ocean for sampling and emplacement of observatories	1%	4%	9%	19%	16%	75	38
Establishment of and long-term support for open-access databases	7%	7%	24%	19%	3%	75	31
Deployment of ultra-long duration balloons	0%	5%	5%	14%	1%	74	55
Deployment of benthic and pelagic oceanic sampling gear	5%	7%	12%	12%	5%	74	43

Appendix 3:
ARC WORKSHOP WRITING GROUP REPORTS

The ARC Workshop was held at the Norwegian Polar Institute, Tromsø, Norway, on 23 and 24 August 2015. Fifty-eight people participated in the Workshop. These Workshop Writing Group Reports are presented as concluded by each of the Writing Groups.

HORIZON SCAN CLUSTER 1:
Antarctic Atmosphere and Global Connections

ARC Workshop Writing Group Participants

Co-leads: Adrian McDonald & Robert E. Wooding

Nicole Biebow, John J. Cassano, Steven Colwell (Scribe), Kelly Falkner, Fang Lijun, Paul Sheppard, Tim Stockings, Qin Weijia

Scientific Questions	*"Changes in Antarctica's atmosphere alter the planet's energy budgets, temperature gradients, and air chemistry and circulation. Too little is known about the underlying processes. How do interactions between the atmosphere, ocean and ice control the rate of climate change? How does climate change at the pole influence tropical oceans and monsoons? How will the recovering ozone hole and rising greenhouse-gas concentrations affect regional and global atmospheric circulation and climate" (Kennicutt et al., 2014 Nature COMMENT).* While the Horizon scan questions are all important without prioritization of questions it is difficult to prioritize the highest priority technological advances. Societal relevance was deemed important as well as the advancement of science. Integration across all questions is important as there are many interconnections between clusters. Expertise within the group limited detailed discussions of paleoclimate related questions. Q72 and Q73 were also somewhat out of the group's expertise, as were Q3, Q5, Q9, and Q53.	
	Highest Priority Technological Advances	
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Observing technology capable of being optimally deployed, sustained autonomously including power requirements.	H
	2. Improved satellite remote sensing.	H
	3. Data transfer in real time.	H
	4. Improved Earth System Modelling for weather and climate modelling and system re-analysis.	H
	5. Improved exchange of people and information across national Antarctic program.	H
Estimation of the current status of the **technology**	1. Mixture of mature and emerging technologies.	H
	2. More deployment of existing sensors required plus some further development.	H
	3. Exists, but not adequately deployed in Antarctica.	H
	4. Mixture of existing and emerging capabilities.	H
	5. Channels already exist, but require strengthening.	H
	Comments: Lessons can be learned from the Arctic community which are ahead in some areas.	
At what temporal scales will these **technologies** most likely be used and how frequently?	1. continuous	H
	2. continuous	H
	3. continuous	H
	4. continuous	H
	5. Increased frequency	H
	Comments: For satellite remote sensing, the continuity of satellite operation is important for climate and ozone records. Atmospheric processes have short time scale and operational links, thus near real time information is important.	

What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Logistics costs of deployment and maintenance are high, so enhanced technology development, although expensive, will improve the observing network and possibly achieve cost savings. Spectrum from 10k to 10M	High
	2. Difficult to identify cost – polar science and operations need to be at the table throughout the time that satellite projects are being developed and implemented	
	3. Polar targeted satellites – 10s of millions. Cheaper alternatives (e.g., Google Project Loon as a communication platform) are under development. Potential to access	
	4. Millions of dollars	
	5. Low-cost: requires active coordination between programs and a will to do it. Coordination between data centers will be important. The costs of investing in this will produce equal or greater benefits.	
	Comments: Satellite specific: COMNAP needs to engage with Experts on Polar and High Mountain Observations, Research and Services. Balance of creation to usage costs and processing for satellite work is important. Polar science giving input to European Space Agency, NASA and other national space agencies.	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	The range of technologies identified are broad and cover most of the questions in this cluster, e.g. Q1, Q2, Q4, Q6, Q7, Q10 and Q11 The technologies identified are more relevant to 'atmospheric' rather than 'paleoclimate' questions.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Satellite development/deployment and ESM development is beyond the capabilities of the Antarctic community. Both need to connect to major other players, (NASA and other space agencies). Development of battery technologies and Unmanned Air Systems are beyond Antarctic community. Both of the latter will benefit from commercial applications/developments.	
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Google Project Loon could be used as an alternative to satellite communications potentially Unmanned Air Systems have not been fully examined in the Antarctic community.	

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority technological needs to accomplish the science of this cluster.	Avoidance of higher cost solutions may not save money long-term. Prioritization based on achievability scientific pay-off. 1. Observing technology capable of being optimally deployed, sustained autonomously, including power requirements. 2. Improved satellite remote sensing 3. Data Transfer in real time 4. Improved Earth System Models 5. Improved exchange of people and information across national Antarctic programs The group considered these to be of equal priority. Discussions were wide-ranging and initially discussed the different questions and their possible technological needs. The survey results were also discussed in terms of their relevance to particular questions. After some discussion it was clear that two of the priorities in the list identified in the survey results, namely 'Continuous measuring sensors' and 'Remote weather stations with expanded and robust sensor arrays' were likely best grouped together because of the intrinsic linkage between Automated Weather Systems and continuous measurements. Technologies for smart deployment are important. Consensus was that many (if not all) questions could be tackled via the use of improved modeling. However, there was significant discussion on whether 'improved climate modelling' was a technological need or a science question. After some debate and examination of the survey results, which showed poor availability of this technology (86% identifying no access), the technology requirement might be considered to be stronger cyberinfrastructure, namely High Performance Computing requirements and the development of relevant databases. 'Improved climate modelling' was changed to 'Improved Earth System modelling' given that developments in this area are moving in this area. An Earth System Model expands the range of the components in the climate system modelled (e.g. adding biosphere, cryosphere). In addition, this change also allows some questions in the Horizon Scan to be tackled (in particular Q4, Q6, Q7 and Q11) also cross-cutting questions (Q19, Q72). Without this broader definition these questions probably cannot be addressed. A significant technological need was to enhance some aspects of logistics with improved operational weather forecasting, thus Q7 in the Horizon Scan is a science question has strong linkages to logistic operations. One member of the group identified that 'it is clear that the Antarctic programs with the best forecasting capabilities completed more work'. There is also considerable replication of this effort amongst national programs. The vital importance of sea ice forecasting logistically was also mentioned, as was connecting to the Arctic community. The World Meteorological Organization's Experts on Polar and High Mountain Observations group was identified as focusing on improving models and data availability. Remote sensing will be a critical technology for answering many questions (Q1, Q2, Q4, Q11). In relation to 'advanced data analysis' a result from Survey 1, improved connectivity (higher bandwidth connections and connecting people) and power technology (a mixture of improved technologies for energy generation/storage and minimization of energy requirements for autonomous systems is absolutely crucial on logistics side) are important. There is a need for 'improved exchange of people and information' – the former may be related to better coordination of the logistic pool, and the latter might be about technology transfer and also better information dispersal and linkages across databases. There was also discussion on the need for deep-ocean drilling for paleo-climate relevant questions but details were uncertain given the group's expertise and these issues are considered by other groups.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Southern Ocean and sub-Antarctic islands	
	2. West Antarctic ice shelf (W)	
	3. The least accessible regions of the Antarctic interior	
	4. Sea ice zone	
	5. Opportunistic access to all areas	
	Comments: Collaboration is becoming more critical between providers. Opportunities were identified – e.g., EU-PolarNet – to link logistics understanding and capability and this could be relevant to future access.	
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. See logistics and infrastructure costings. Millions of dollars per ship voyage, hundreds of thousands to millions of dollars per traverse/aviation activity.	
	2. Hundreds of thousands to millions per traverse/aviation activity.	
	3. Hundreds of thousands to millions per traverse/aviation activity.	
	4. Icebreakers – millions per voyage.	
	5. Low cost – transfer of equipment and knowledge to a science or logistics team visiting a particular area.	
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	The regions identified support all 11 atmospheric science questions.	
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **accessed** to accomplish the science of this cluster.	Many questions are linked to teleconnections at hemispheric scale, and can only be addressed through broader sampling from a larger range of areas, including large parts of the Southern Ocean, the West Antarctic ice shelf and some of the least accessible inland parts of East Antarctica and Dronning Maud Land. The last of these areas feature the most extreme climates on the planet. Data collected from the sea ice zone will be particularly important for understanding interactions between cryosphere and atmosphere, ozone chemistry, air-sea flux changes. EU-PolarNet and the need for improved coordination are key for opportunistic access. Teleconnections work should likely consider the tropical to polar influence as well as the polar influence on the tropics.	

Highest Priority Infrastructure and Logistics

What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Ships – dedicated voyages, giving year round access to the Southern Ocean, the sea ice zone and the continental coast.	
	2. Integrated traverse and aviation capability.	
	3. Temporary or permanent bases to enable data collection from the West Antarctic Ice Sheet.	
	4. Deployment of drilling capability – particularly for sub-ocean sediment.	
	5. Opportunistic instrumentation on under way vessels and aircraft.	
	By "infrastructure and logistics", the group is referring to Antarctic stations and transportation. Information and Communications Technology infrastructure is covered under "technology". Others/comments/variances from ARC survey results. Nations wishing to build new stations could be encouraged to focus on West Antarctica. Alternatively, given that the area is also a high priority for ice sheet scientists, perhaps a multi-national expedition or station could be established there. Instrumenting under way vessels might be particularly useful for collecting CO_2 data. Drilling of ice cores is seen to be a well-developed activity, with plans already in place. Data availability was also seen as important, but possibly not largest infrastructure requirement	
What are the estimated costs of providing enhanced **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Dedicated voyages are expensive: hundreds of thousands per week. Ships capable of working in sea ice are important: while some new, more capable, vessels are coming into service, the total number of highly-capable icebreakers globally is in slow decline. New ice-capable vessels cost hundreds of millions of dollars.	
	2. Hundreds of thousands to millions of dollars for a one off traverse. Cost changes marginally for repeat traverses.	
	3. New permanent inland stations and/or stations in difficult areas such as the West Antarctic Ice Sheet can cost many 10's of millions of dollars to build and the ongoing operating costs and risks are high. Temporary and/or portable solutions could be much more cost-effective.	
	4. Requires an escort icebreaker if in sea ice zone (possibly more relevant to Arctic), which means a cost of many millions, even tens of millions.	
	5. Range from thousands to hundreds of thousands of dollars to equip aircraft and ships.	
	Comments: China is bringing new capabilities, especially to East Antarctica: a new icebreaker, a new intracontinental aircraft and repeat traverses to Dome A. All of these capabilities could be used to take observations from new areas, including through the positioning of AWS. New German and Australian icebreakers with moon pools and, possibly in the case of Australia, advanced drilling capability, are planned.	
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All questions.	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	Opportunistic voyages provide relatively low cost access which enhances observational networks in the Southern Ocean. Also supporting real time forecasting is of direct benefit to improved efficiency of resources. However, there are key types of observations, particularly for understanding broader processes, which will require dedicated voyages/expeditions.	

Summary and Conclusions	
What are the top 10 “take home messages” from your discussion, i.e., the “big issues” including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Cooperation across scientific disciplinary boundaries will be particularly important for the cost-effectiveness of deployment and scientific efficacy.
	2. The power technology challenge is critical and cross-cutting.
	3. Need to enhance links between atmospheric research, modelling and operational forecasting, for mutual benefit.
	4. Integrated system science is crucial to progress modelling.
	5. Communication between the polar community and national space agencies/ remote sensing community is vital for improved satellite monitoring.
	6. Cooperation among national providers will be key to big science issues and access to remote regions
	7. Past and future data sharing, distribution and standards are important.
	8. Improved monitoring of the climate and weather systems of the Southern Ocean is vital to understand global connections.
	9. Real-time data crucial for some disciplines.
	10. Winter operations key for process level studies.

HORIZON SCAN CLUSTER 2:

Southern Ocean and Sea Ice in a Warming World

ARC Workshop Writing Group Participants

Co-leads: Anna Wåhlin & John Hall
Stephen F. Ackley, Lautaro Jimenez Corbalan, Chen Danhong, Alexander Klepikov, Joohan Lee, Mariano Memolli,
Miguel A. Ojeda Cárdenes, Simon Trotter, Gary Wilson (Scribe)

<table>
<tr><td>Scientific Questions</td><td colspan="3">The Southern Ocean has crucially important roles in the Earth system. It connects the world's oceans to form a global system of currents that transfers heat and CO_2 from the atmosphere to the deep ocean. Nutrients carried north support a large part of the ocean's food web, and [the sea ice cover provides an important habitat with a high concentration of algal biomass and krill.] The ocean is becoming more acidic as CO_2 dissolves in sea-water, and cold southern waters will be the first to exhibit impacts. How will climate change alter the ocean's ability to absorb heat and CO_2 and to support ocean productivity? Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? How will the biological pump change? Why have the deepest waters of the Southern Ocean become warmer and fresher in the past four decades? [Closely coupled to the ocean and atmosphere, sea ice and its snow cover reflects and filters sun light. The ice and snow cover modulates heat, momentum and gas exchange between the ocean and atmosphere.] Sea-ice formation and melt dictate the salt content of surface waters, affecting their density, [stratification] and freezing point. What factors control Antarctic sea-ice seasonality, distribution and volume? We need to know. [The ice-shelf-ocean system needs to be understood and active processes quantified. The Antarctic Ice Sheet is the largest source of uncertainty in predictions of future sea-level rise. The Antarctic ice sheet loses mass at the coast from iceberg calving but a significant part is also lost from melting at the base of its coastal floating glaciers (ice shelves). This basal melt is caused by warm ocean currents circulating below the ice shelves and accessing the glacier underside. Ocean warming thus plays a primary role in determining the future behavior of the Antarctic Ice Sheet. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean? What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice and how has it changed historically? How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing? How will changes in freshwater inputs alter ocean circulation and ecosystem processes? How did the Antarctic cryosphere and the Southern Ocean contribute to glacial-interglacial cycles? These questions need to be addressed in order to improve future sea level predictions and other consequences of a changing glacier influx to the Southern Ocean.] –
Modified from Kennicutt et al, 2014 (<i>Nature</i>)</td></tr>
<tr><td colspan="4">Highest Priority Technological Advances</td></tr>
<tr><td rowspan="7">What are the highest priority technological needs to answer questions in this cluster?</td><td colspan="2">Rank Order (1 is highest priority)</td><td>Confidence (H,M, L)</td></tr>
<tr><td>1.</td><td>Underwater (and under floating ice) navigation and positioning.</td><td></td></tr>
<tr><td>2.</td><td>Bandwidth and continuity of data communication from remote locations (specifically underwater including under ice).</td><td></td></tr>
<tr><td>3.</td><td>AUVs, gliders and UAVs with greater range (6000 km or more) and capacity.</td><td></td></tr>
<tr><td>4.</td><td>Long-term ice and deep-water capable sensor platforms and networks of platforms (including ice tethered platform/profilers, sea ice buoys, drifters, moorings and observatories).</td><td></td></tr>
<tr><td>5.</td><td>Unmanned physical and biological sensors and groups of sensors (power needs/ greater efficiency).</td><td></td></tr>
<tr><td colspan="3">Comments:
• Fit-for-purpose satellite and UAV sensor and capability development (e.g. sea ice thickness)
• Development of improved instrumentation for deployment on marine mammals
• Using biological indicators as proxy for large-scale shifts in ocean and atmosphere dynamics (scientific challenge but it would help solve the technological challenges of measuring and tracking the marine environment) – e.g. genomics –see the life on the precipice group report.
• Sediment cores – see the solid Earth group report.</td></tr>
</table>

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Partially exists – not widely available, range limited. 3-9 years to develop fully.	H
	2. Technology exists – but not for appropriate bandwidth and range needs – additional challenge is applicability to the Antarctic setting. 3-9 years to develop fully.	H
	3. Technology is partially in development, greater range of sensors and power capability is yet to be developed – additional challenge is applicability to the Antarctic setting. Communication challenge yet to be solved. Development is ongoing.	H
	4. Technology partially exists but not readily available and only partly adapted for the Antarctic setting. Long term challenge yet to be solved. Development is ongoing.	H
	5. Some technology available but not in a comprehensive way. Much work yet to be done on biological sensors. Still a power and communication challenge. >10 years to develop fully for biology, less for physical observatories.	M
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	1. Continuously & long term	H
	2. Continuously & long term	H
	3. Measuring continuously but deployed monthly over a long term	H
	4. Measuring continuously but deployed seasonally or annually over a long term	H
	5. Range between continuous and annual for the long term	H
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. $1-10 million USD	L
	2. >$10 million USD	L
	3. $1-10 million USD	M
	4. $1-10million USD	M
	5. No estimate	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/ which questions (by Horizon Scan number)?	Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31, Comment: Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	The communication challenge will require all national programs to work together. The network of coverage and range of environments to be studied will need collaboration of multiple programs. Links to commercial and military entities will be helpful for technological development and technological availability.	
Are there **technologies** and/ or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	No for the top 5 but yes for some of the others – e.g. genomics, continuous. No for deep sediment sampling.	

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	An overarching goal is to move towards much greater automation of measurements and lessening the dependency on ice breakers to perform field work. Several of the technological improvements to move towards greater automation are common between the various platforms (e.g. AUVs, gliders, UAVs, ROVs, floats, drifters, etc) and also common to several other groups. For example, underwater (and under ice) navigation and positioning is needed in order to access the under ice environment. Developments in this field are underway and prototype stage technology exists, but it needs to be made more accurate, longer range, and more available. A community-driven strategy for development in this area is presently coordinated by SOOS. The next over-arching technology that needs to be developed is bandwidth and transfer of large data quantities from Antarctica, including for the marine realm the challenge of transmitting through the ocean itself. Presently this can be done with cable, with sound (limited bandwidth), or through the release of data capsules to the surface. A common and affordable technology for all science fields to transfer data from Antarctica via satellite or high-altitude UAVs is a priority development. The goal of much greater automation of measurements will be limited by bandwidth. Moving towards greater automation will also require better power supplies. Presently technology such as AUVs, UAVs and gliders are limited in range by the power supply. Developing smaller and more powerful batteries, alongside making sensors smaller, cheaper, less power consuming and more modular will make it possible for a new generation of long-range AUVs, UAVs, gliders and animal-borne sensors for the Southern Ocean, its sea ice cover and the under-ice shelf environment. Also and in an effort to move towards greater automation and less dependency on ice breakers is the need to develop long-term networks of buoys, moorings, ice-tethered platforms (including ice buoys) and drifters. Current moorings can be left at sea for about 2 years. In the future at least 5 years duration at sea will be needed. This requires developing the power supply and making long-term stable sensors. Drifter networks do presently exist but they need to be developed for under-ice environment (i.e. the navigation/position capability), for deep sea environments (larger pumps), and for shallow environments. Ice-tethered platforms (including ice mass balance buoys) need to be of longer duration. Unmanned observatories can act as hubs where a multitude of observations (weather station, ice radar, ocean measurements cabled up from moorings, gliders/AUVs, UAVs or buoy networks) are powered and data collected and transmitted via satellite link external to Antarctica. Satellite measurements were discussed and it was agreed that they are very important, and provide perhaps the only presently existing long-term measurements in the area. However, it was also recognized that they need to be ground-truthed, and that there will always be a need for complementary data being collected, e.g., at better resolution or of properties of the interior medium like below the ocean surface and below snow layers on sea ice. Presently the only way to obtain winter-time data of the surface waters of Antarctica is through instrumented mammals. The technology for this exists, although it needs to be made more widely available (i.e., less expensive). The questions about paleoclimate, and extreme events, need to be addressed by studying the deep sediment record presently only available with core drilling, which is a technology that exists but is not yet readily available for use in Antarctica. Studying biology as a proxy for physical properties is an alternative to technology that needs to be better explored and exploited both for present and past climatic settings.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access** ?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Winter / year-round access to the continental margin / shelf edge including important polynyas.	H
	2. Beneath floating ice (sea ice and ice shelves).	H
	3. Circum-Antarctic coverage (specific problems for specific regions).	H
	4. Deep-water.	H
	5. Year-round nearshore access.	M
	Comments: Current areas of high interest include the Ross Sea sector, West Antarctic, Prydz Bay, the Totten and Mertz Glacier regions of East Antarctica, Amundsen Sea, Weddell Sea Sector, and Islands. Marine environmental management, while a scientific need, will potentially drive specific areas of interest.	
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. >$100million USD – requires ice breaker availability and glider/AUV development.	H
	2. $1-10million USD – glider/AUV navigation and hot-water access for mooring network – support from traverse.	M
	3. Mostly better use of existing access networks (e.g. ship track planning, island and coastal stations).	M
	4. Development of autonomous capability/capacity and better use of existing access networks (e.g. ship track planning, island and coastal stations) – $1-10 million USD.	H
	5. Relatively inexpensive where existing stations are available (<$1 million USD), requires significant infrastructure investment where not available ($1-10 million USD).	M
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31, **Comment:** Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements).	

Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access** ed to accomplish the science of this cluster.	The most significant access challenge for measuring the Antarctic and Southern Ocean is year round access and in particular winter access. Circum Antarctic coverage is also desirable to generate a more comprehensive understanding of ocean-sea ice-atmosphere interaction processes and interaction with the ice sheet and the sub-sea geological substrate. There are areas of current interest and focus, particularly the large embayments fringed by floating ice shelves. Technologically this presents a conundrum as winter access requires a move to more expensive research capable ice breakers but this may come at the cost of wider temporal and spatial coverage of measurements. Some of this challenge may be addressed by autonomous underwater and airborne vehicles but this may drive more specialized and exclusive measurements types at the expense of broader platforms for a range of scientific and technological challenges. Other access priorities are to develop greater understanding of oceanic and linked cryospheric processes and links to global and biological systems including deep sea and near-shore Antarctic access. The cost of obtaining this access varies – where proximal to existing stations and ship tracks, the cost may be as simple as negotiating better collaboration between national programs. However, there is a challenge to access environments and regions beyond the reach of traditional Antarctic stations and the requirements to access those may range from development of remote observation technologies to unmanned observatories to new temporary research stations. Consideration also needs to be given to accessing continuous deep sediment records from beneath a range of Antarctic marine environments; to carry out extensive bathymetric mapping at high resolution.

Highest Priority Infrastructure and Logistics

	Rank Order (1 is highest priority)	**Confidence (H,M, L)**
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	1. Greater continuity, coordination, and year round access of research capable ice-breaker(s) – requires international collaboration.	H
	2. Marine and sea ice observatories in high science priority areas (e.g. Islands, Amundsen Sea, Western Weddell Sea, Bellingshausen Sea, and the Eastern Ross Sea) making appropriate measurements.	H
	3. Data infrastructure (data sharing and data management systems).	H
	4. Underwater docking ports to support AUVs, gliders, and moorings.	H
	5. Improved co-ordination of bathymetric data collection.	H
What are the estimated costs of providing enhanced **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. >$100 million USD for year round access – better coordination of current access.	H
	2. $10-100 million USD.	M/L
	3. $1-10 million USD – most cost is in the infrastructure development rather than managing the sharing.	H/M
	4. $1-10 million USD ~$1 million USD each.	M
	5. No cost – just agreement to collaborate and work together, perhaps small marginal cost for taking slightly longer ship tracks.	H
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31. **Comment:** Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements.	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	An overarching goal is to move towards much greater automation and thus in the process reduce infrastructure footprint. However, the most significant access challenge is year-round access and in particular winter access to scientific priority areas that are not currently monitored and observed on a regular basis. In order to achieve the Circum-Antarctic coverage for scientific observation and data collection new observatories (manned or unmanned) will need to be established in high priority coastal areas that currently do not have observatories. There is also an opportunity through international collaboration to encourage existing coastal stations that do not undertake nearshore marine observations to consider doing so in the future. It is also recognized that there is still an ongoing requirement for better, more focused and coordinated year-round access by research capable ice-breakers. In order to extend the range and utilization of UAVs, gliders and moorings underwater docking ports could be explored & developed. Such docking stations could enable data download and power provision. Linked to shore stations and or fixed moorings such facilities could transfer data via satellite link. Some of the infrastructure & logistics challenges are already being addressed by international collaboration but there is an ever increasing requirement to improve such collaboration and integration. Improved coordination and collection of bathymetric data with more effective targeted campaigns is the only way to fill major gaps in the bathymetric data, needed for accurate models of the Southern Ocean. Likewise more effective sharing, management and transfer of data is a major requirement now and into the future.	

Summary and Conclusions	
What are the top 10 “take home messages” from your discussion, i.e., the “big issues” including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Access beneath floating ice (sea ice and ice shelves) is emerging as a common goal to solve a wide range of science priorities.
	2. Greater automation – e.g. AUVs and gliders with greater range and unmanned biological and physical sensors/observatories.
	3. Underwater (and under floating ice) navigation and positioning and communication including docking station development.
	4. Ship access is a significant requirement that will need greater international collaboration. Greater continuity, coordination, and year round access of research capable ice-breaker(s) is needed. Icebreaker instrumentation and its coordination and standardization is also a consideration. .
	5. Long term Ice and deep-water capable buoy networks (including ice tethered platform/profilers, sea ice buoys, drifters and moorings).
	6. Need for new sensor technology (at all levels from in-situ to satellite).
	7. The challenge of big data – data bandwidth and transfer rates including underwater transfer.
	8. Greater collaboration is needed with external agencies (e.g. commercial and other governmental organizations) to help develop and apply new technologies and solve the communication and data transfer challenge.
	9. Many of the groups identified similar access requirements to high science priority areas – e.g. Antarctic embayments (with floating ice shelves & sea ice), Islands and less explored regions. There is also a requirement for access from the deep ocean and across the shelf to nearshore environments including ice shelf cavities.
	10. The challenge of mismatch between position of stations and locations being considered for future science measurements/experiments/observations – solutions will come from multiple approaches, e.g. greater automation, the development of modular and relocatable systems/facilities, new temporary stations and greater interoperability.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	Increasing availability, miniaturization, and modularization of technology. Increasing access to satellite derived data.
Additional comments	International collaboration and diversity of approach is going to be essential to increasing measurement coverage and resolution. The opportunity to develop proposals and gain science funding jointly between international partners would be extremely helpful in developing the collaborations and sharing resources. While the role of modeling in achieving the science goals is understood, considerations were focused on the technological developments, access and infrastructural and logistical needs in Antarctica. While satellite developments were only peripherally considered, the need for inclusion was recognized to address southern ocean and sea ice challenges in the Antarctic. Satellite based methodological development is underway and a greater need for routine data collection and ground-truthing to support satellite coverage and interpretation was deemed important. There are also opportunities for cooperation with the dynamic earth and the atmosphere group and crosscutting solutions are important from paleoclimatic and paleoceanographic approaches – especially horizon scan questions Q20, Q21 & 45.

HORIZON SCAN CLUSTER 3:

Antarctic Ice Sheet and Sea Level

ARC Workshop Writing Group Participants

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Scientific Questions	*"The Antarctic ice sheet contains about 26.5 million cubic kilometers of ice, enough to raise global sea levels by 60 meters if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO_2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown." Kennicutt et al., 2014 Nature COMMENT*
Highest Priority Technological Advances	
	Rank Order (1 is highest priority)
What are the highest priority **technological** needs to answer questions in this cluster?	1. **Process driven numerical ice sheet modelling** Various aspects of modelling need to be developed, including better accounting for: a. bed topography and characteristics (needed as a vital model input), b. surface mass balance (needed as a vital model input) c. basal conditions (to avoid current situation where they are calculated internally with little attempt to link with real data), d. ice structure, fabric and anisotropy (see #2), presently unaccounted for, with no attempt to link with data (layers, polarimetric radar etc.), e. ice and geothermal temperatures, f. basal hydrology, g. distribution of basal sediments, h. 3-D flow of ice (little if any link with internal layering), i. grounding lines/zones, j. Ice shelf modelling and iceberg calving with coupling between ice/water/atmosphere, and k. lithospheric treatment (GIA) Limitations in ice sheet modelling is a major aspect of the uncertainty in predicting and understanding ice sheet change and sea level rise. Model development needs continued coupling between the glaciological modelling and observation communities.
	2. **Subglacial sampling –** where short-term (on the order of days) rapid, reliable, clean access is required, sampling at or near the ice-bed interface.
	3. **Combined multiple geophysical measurement and sampling of ice.** Ice fabric development and its rheological implications. To understand numerous subsurface properties from measurements conducted at the surface including deep ice core and paleoclimate record recovery.
	4. **Satellites making synoptic, operational measurements of snow and ice accumulation.** Needed in conjunction with targeted field observations, including SMB and GIA, to yield accurate surface mass balance fields.
	5. **Autonomous sensors** remotely deployed and remotely accessed, acquiring information on ice shelf bathymetry and ocean conditions. For example, grounding zones.
	6. **Subglacial sediment recovery.** Where deep core material is collected, requiring long-term access to the bed (on the order of weeks).
	7. **Greater use of AUVs** (autonomous unmanned vehicles – submersible). AUVs campaigns can be guided by airborne gravity and seismic data to map ice shelf bathymetry in detail in key regions. Oceanographic time series measurements of water temperature, currents, salinity, turbidity, etc. under the ice shelf.
	8. **UAVs (airborne) with geophysics**, including Swath radar allowing 2-D mapping of ice sheet bed and conditions.
	Comments: Open data policies, perhaps also push for open technology policies. Open discussions between engineers, technologists and scientists through international collaborations.

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1.	The major limiter for ice sheet modelling is the lack of observations, both for model input and to understand ice sheet processes not adequately modelled at present. For ice sheet fabrics no models exist due to the lack of field data; for bed conditions, ice sheet models perform poorly due to scarcity of measurements; for ice shelf processes, calving laws and ice-ocean interaction is poorly known. For ice and bed temperatures: models do exist, just not applied regularly due to computational cost. Lack of observations are holding model development back. Next generation of models are needed, and ice sheet modelling needs to be scaled up, along the lines of global climate modelling. Modelers must integrate with observational glaciology. Substantial improvements in numerical ice sheet modelling are needed.
	2.	Subglacial sampling at (or near to) the bed – technology does exist, but not widely available. Not for regular measurements, but cleanly, at certain depths (currently ~800m). Access at greater depths (e.g. RAID) allows access to the frozen bed but is not (yet) clean. 5-10 years to achieve clean sampling to greater (~3km) ice depths.
	3.	While multiple geophysical techniques have been deployed in Antarctica, they have seldom been used collectively in a targeted manner, due to operational and logistic limitations. Technological advances in geophysics, (e.g. reducing the need for wires, mobile seismic sources, polarimetric radar) are now available for this purpose. 5 years to perform a showcase exercise, demonstrating the utility and feasibility of the approach.
	4.	Snow accumulation data from a satellite – 10 – 20 years, doesn't exist at present.
	5.	Remotely deployed instruments (for challenging regions, e.g. grounding zones) – technology exists, 5 – 10 years away, not widely available, need higher resolution technologies.
	6.	Subglacial deep sediment recovery – some technology exists (e.g. ANDRILL), but not widely available and never tried on ice sheets. 5 – 10+ years.
	7.	AUVs underwater, to measure ice shelf cavities. Technology exists, some development still needed 5-10 yrs. away.
	8.	UAVs airborne. Ice sheet topography/basal conditions. Technology exists, some development still needed 5-10 yrs. away.
		Comments: In 20 years these technologies need to be routinely deployable. Open data policies will be needed to allow processing of the 'big data' created.
At what temporal scales will these **technologies** most likely be used and how frequently?	1.	Ice sheet modelling – not applicable to this question.
	2.	Subglacial sampling – dependent on access, technology and cleanliness protocol. A small number/year.
	3.	Geophysical measurement and sampling. A small number/year.
	4.	Snow accumulation from satellites – at least 30 day repeat or better, for multiple years. Potential big data implications.
	5.	Remotely deployed and operated sensors (e.g., grounding zones) – types of measurements vary, short term use (max 2yrs), sending real time information every few minutes. Potential big data implications.
	6.	Subglacial sediment recovery – dependent on access, small number/year – but has to be done within a season.
	7.	Underwater AUVs (for ice shelves) – seasonally, potentially year round.
	8.	Airborne UAVs (for ice sheet geophysics) – potentially all year round.
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1.	Modelling – $10+ million USD to set up comprehensive system.
	2.	Subglacial sampling – ~$10+ million USD.
	3.	Combined multiple geophysical measurement and sampling of ice – ~$10 million USD.
	4.	Satellite – ~ 150 – 300 million USD, plus launch costs.
	5.	Autonomous sensors – technologically money to be invested in development ($1-5 million USD), once available there will be a significant savings in production.
	6.	Sub glacial sediment recovery – dependent on sampling target. $1 – 10 million USD, depending on target.
	7.	AUVs – similar to sensors, multi million for development, but scaling down once developed. Key is robustness for deep diving. $5 – 10 million USD.
	8.	Airborne UAVs – 5 million USD to equip UAV with full geophysics suite. $5 – 20 million USD. Smaller ones are $1M to develop, $100,000 USD to fly. The price depends on the platform and scale – small cameras on a remote controlled UAV up to Global Hawk at $20 million USD.

Will these **technologies** support multiple scientific questions in this cluster? If so, how many/ which questions (by Horizon Scan number)?	1. Ice sheet modelling – 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 2. Subglacial sampling – 25, 26, 27, 32 3. Combined geophysical measurements and sampling – 24, 25, 26, 27, 28, 29 4. Satellite – 25, 29, 31 5. Autonomous sensors – 24, 25, 26, 27, 29, 30 6. Sub glacial sediment recovery – 25, 27, 32, 33, 34 7. AUVs (water) – 24, 25, 26, 28, 30, 31 8. UAVs (airborne) 24, 25, 26, 27, 28, 29, 30, 31 Also, relevant to Qs in other sections, such as 7, 8, 38 and 40.
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Outside of NAP: Satellites, AUVs and UAVs. Subglacial access won't be used for anything else, so within NAP capabilities. Instruments on and platform for AUVs and UAVs are probably beyond an NAP. All these technologies could be deployed in Greenland. Global ocean and climate modelling will not be completed by NAP, but it is essential for Antarctic models. Development of coupling of ice model to any of the global models needs collaboration between international institutes.
Are there **technologies** and/ or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Yes. Widely accessible high band width communications. If UAV or AUV could pop up and link in, that would be transformative. A Sub orbital (non-satellite) system is needed. Such data communications and networks exist outside of the Antarctic. For example, a sequence of balloons could provide bandwidth on the ice – and is being done in South America right now. Arctic Council recently established task force to investigate communication satellite development – Antarctic community could have some advantage of that in future. Power management systems (fuel cells, batteries, flex solar panels, wind generators) for remote observatories/stations. All this is low tech and available, but not enough for purposes required (batteries don't last long enough etc). Miniaturization of Automated Weather Systems and GPS technologies. High cost due to small market, need to advertise outside of Antarctic to increase market and decrease cost. Automated Weather Systems and GPS already as small as they can go. Batteries still need development. There are people who work solely in miniaturization who do not work in Antarctica. If they did, that could be transformative. Wireless Geophones; 3-D seismics. Exists now, could be imported from exploration industry.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	Understanding Antarctic ice sheet and sea level change requires ice sheet modelling for predictions, making such modelling a key priority in this section. Ice sheet models have improved considerably over the past 20 years, but substantial improvements are needed to better constrain predictions and reduce uncertainty. Such improvements are mostly constrained by lack of knowledge/observation relating to key processes, underlining the need for modelling and field data acquisition to be coupled. High confidence that ice sheet modelling is capable of describing the real flow of ice in Antarctica, including all relevant processes, and that this can be achieved over a 20 year timescale. While ice sheet modelling is a priority, these other items are not prioritized in order. a. Knowledge of ice and snow accumulation rates is poor and requires satellite measurements to make the advance in observations necessary. b. Ice sheet flow is affected by basal processes and ice rheology, both of which are not well described in models. To obtain the necessary observations, sampling of the subglacial environment and englacial environments are needed. To guide sampling, geophysical imaging of the ice sheet is needed. c. Critical regions of the ice sheet, such as grounding zones and shear margins, are challenging for deployment of personnel. Solutions here involve the use of remotely deployed expendable instruments. d. Also critical to ice sheet change are ice shelf and grounding zone processes, requiring both on ice and sub-ice shelf measurements. The interface with oceanography being important here. e. Knowledge of past ice sheet changes require samples of ice and basal sediment, guided by improved geophysical measurements. f. Potential exists to use unmanned aircraft to expand geophysical data coverage. Also, industry standard 3-D seismics could offer transformative insights into basal processes and ice structures. g. Miniaturization of equipment, undertaken in other areas of science (e.g. space science) could be used well for Antarctic purposes, offering important savings on weight and power, and extending the time series of measurements. h. All of the technological advances discussed above are pertinent to more than one of the Horizon Scan questions in this section. Some of them, ice modelling and geophysical measurements, and ice/sediment sampling, are relevant to most of the questions. Others, underwater vehicles are linked strongly to oceanography use and, hence, the oceans section. i. Finally, with the enhanced communications being used regularly in other geographical regions, and with the coming 'big data' from instruments (in real time and enhanced resolution), sub orbital communications networks are seen as an important step for the next generation of ice-sheet measurements.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access** ?	**Rank Order (1 is highest priority)**
	1. Amundsen Sea Embayment, basin. Thwaites Glacier System, West Antarctic.
	2. Deep marine margin-interior of ice sheets, including grounding zones.
	3. Deep interior Antarctic Plateau.
	4. Coastal islands and ice rises. Obtaining paleoclimate from coastal regions, and deep time from the interior. Blue ice – Including horizontal ice coring.
	5. Sedimentary basins, for their value in obtaining process information and sedimentary records.
	6. Ice shelf cavities/systems.
	7. Shear margins – records of ice sheet change within the system.
	Comments: Geographical regions were identified as being important as a consequence of observed changes. We are unable to predict in twenty year time period which other regions may experience change and therefore it is necessary and wise to obtain measurements in places potentially vulnerable.
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Thwaites Glacier – could do a lot for $20 million USD per year, over 5 years. $100 million USD.
	2. Marine portions >$–10 million USD per year per geographical region e.g., Wilkes, Totten
	3. Interior ice – $60 million USD.
	4. Ice rises, coastal – approx. $2 million USD, but it is dependent on proximity to existing facilities.
	5. Sedimentary basins >$10 million USD.
	6. Ice shelf cavities/systems $5 – 10 million USD per cavity.
	7. Shear margins – depends on how adventurous one wishes to be. Autonomous network ideal – $1-2 million USD.

If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	1. Thwaites – 24, 25, 26, 27, 28, 29. 30, 31, 32, 33, 34 2. Marine ice sheets – 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 3. Interior ice – 24, 25, 26, 27, 28, 32, 33, 34 4. Ice rises, coastal ice – 24, 25, 27, 28, 29, 30, 31, 32, 33, 34 5. Sedimentary basins – 24, 25, 26, 27, 32, 33, 34 6. Ice shelf cavities/systems – 24, 25, 26, 28, 29, 30, 31, 34 7. Shear margins – 24, 25, 26, 27, 28, 32, 33
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access** ed to accomplish the science of this cluster.	The highest priority is access to regions of the Antarctic that are either currently contributing significantly to sea level rise, or will likely do so in the century to few-century time scale. Glaciological models and theories identify marine ice sheets (those parts of the ice that are grounded below sea level) and the grounding zones fronting those ice sheets as the most vulnerable to rapid and irreversible change. Thwaites Glacier and its surrounding grounded ice and glaciers, ice-shelves, and the Amundsen Sea are currently undergoing rapid change and are identified as the highest access priority. In order to study the system, extended-season access is needed to the ocean and ice-shelf environments; access to the difficult grounding zone is necessary; extended-season access to the interior for geophysical, drilling, and sampling work is needed. Though Thwaites Glacier is currently undergoing change, there are numerous marine ice-sheet basins in East and West Antarctica that may do so in the future. Measuring, modeling, and monitoring these as baselines for their current configuration, and for better assessment of their eventual rate of contribution to sea level is needed. Access to these basins (Wilkes, Totten, Amery, Getz etc.) is a high priority. These marine ice sheets are linked to the internal reservoir of the full Antarctic Ice Sheet, and understanding the full contribution to sea level requires access to the interior. The distribution of subglacial sedimentary basins and the properties of those basins has an influence on the flow of the ice sheet and of the ability of the ice sheet to stabilize against perturbations from, e.g., ice shelf or grounding line changes. In addition, sedimentary basins contain a record of past changes that can improve understanding of the response of the ice to well-known climate forcing. The stability and configuration of ice shelves that fringe marine ice sheets are one important control on the contribution of that ice to sea level change. Understanding ice shelves and the adjacent grounding lines requires access to a complex and dynamic region of sea-ice and icebergs on the one hand and crevasses on the other. Access to this part of the system is critical and will require technological innovation and significant logistic effort. In similar manner, lateral shear margins of glaciers (which separate rapidly flowing ice from slow-flowing ice) are poorly understood features of the ice sheet. They are difficult to access because of crevasses, but technologies similar to those proposed for grounding zones and ice shelves could be used here.
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	1. Lengthen operation window for field work. Doubling length of season could double progress of science, not amount. 2. Mobile and temporary stations. Fixed assets could be less than optimal due to changes in science direction based on observations and modelling. Need stations that are deployable into difficult areas, and moveable. Should be achievable on 20 year scale, e.g. high priority Thwaites Glacier. Similarly, developing inland/plateau traverses – especially with electrical tractors and sledges which hold the buildings, will maximize trans-Antarctic science. 3. Fuel efficiency. More efficient deployment of fuel AS WELL AS alternative/renewable energy sources. Innovations in solar panels and power systems for large bases. 4. Communications – sub orbital network. 5. Stronger, recognized and organized framework for transnational collaboration and logistic uses (e.g., perhaps similar to SIOS, INTERACT). Need to find right mechanisms and still keep domestic priorities, maybe by pooling of national resources. Polarstern example is optimal. Increase international cooperation and support for logistics. 6. Multilateral research council co-funding agreements.
What are the estimated costs of providing enhanced **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Mobile stations – 10+ million USD (capital investment) 2. Fuel efficiency measures and renewable sources saves money 3. Communications – see earlier estimate 4. Recognized international network of logistics – doesn't have a cost, just do it 5. Research council co funding agreements – doesn't have a cost but will likely be met with resistance. Can only happen with multilateral scientific imperatives, which individual nations cannot achieve on their own. 6. Field season – cost of achieving this can't be estimated, but the likelihood is it will produce efficiencies/savings long term

If available, will these infrastructure and logistical needs support multiple scientific questions in this cluster?	1. Field season length 2. Mobile stations 3. Fuel efficiency 4. Communications 5. Recognized logistics network 6. Research council co funding All apply universally to the research questions in this section
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	The contribution of Antarctic ice sheet to future sea-level rise, is an issue with immediate and global significance, with impacts to lives and livelihoods in coastal communities and economies around the world. The urgency surrounding these issues, will be reflected in the requirements placed on logistics and budget support in Antarctica. The development of an optimal logistical capability to support rapid progress in ice sheets and sea-level research will require attention to technological advances, planning of key infrastructure and a removal of barriers, to multidisciplinary science, to effective international and inter-agency collaboration, the cooperative development of science strategies, in the joint/cooperative allocation of funding, and crucially in sharing of logistics support. Many recent advances have been achieved through satellite and airborne remote sensing, and an ongoing capacity is a prerequisite for rapid progress in this field; ensuring this capability cannot be overlooked as a task for polar science. In the last decade, rapid advances in observation and modelling have created high-priority targets for research, which are both geographically glaciologically specific. These will persist for at least another decade, but over the coming 20 years it is likely that other priorities will arise, and this expectation demands flexibility in logistic capability and planning. In many areas, technologies that are developed for one-off experimental campaigns will be required to achieve, an operational status, either deployed to multiple sites or established as long-term monitoring stations. Such sampling is needed over wide geographic areas, and over periods of many years in order to provide the density of sampling required to inform ice-sheet projections. Much of the work needed to support ice-sheet modelling will continue to be remote from permanent stations, and this will need to be supported by mobile and remote field-parties, and through remotely operated sensors and rovers. The efficiency of these parties (rapidity, scale and duration of deployments) should be improved (e.g., through appropriate cold-hardening, and deployment/support options). Innovation in the logistic technology available to support of field activities, through flexible, and rapidly deployable facilities (e.g. traverse parties, field camps, moveable stations) may require cooperative development.
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return? ** T= Technical Issue ** L = Logistical Issue	1. Modelling coupled with observations; next generation ice sheet model, capable of describing the real flow of ice, linked with ESS models. Predicting change is the goal. Bed topography, fabric, heat flux, sediments, temperature, etc. (T)
	2. Access to interior Amundsen Sea embayment ice sheet, ice shelf and grounding zone, to make the observations needed to drive models. (L, T)
	3. Recovering datable subglacial material revealing details on the last deglaciation of all, or part of, West Antarctica. (L)
	4. Comprehending palaeoclimate signal from the basal layers (thinned and sometimes disturbed ice). Requires rigorous high resolution site selection geophysics and modeling and detailed analysis of ice-core material. (T, L)
	5. Characterizing Antarctic ice shelf cavities, from grounding zone to continental shelf systems (including subglacial discharge, iceberg production, transport and melt), around the continent. (T, L)
	6. Real time remote data recovery (in challenging locations, e.g. grounding zones and shear margins). (T)
	7. Understanding the spatial/temporal evolution of subglacial water systems, and the consequences for ice flow. (T)
	8. Ability to rapidly deploy to potentially changing regions, e.g. deep subglacial marine basins, with benchmark knowledge to constrain changes. (L)
	9. Comprehensive surface mass balance measurements. (T, L)
	10. Knowing the flow of ice in vertical profile in all places from interior to grounding zone. (T, L)

Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	a. Miniaturization of sensors. b. UAVs (air). c. AUVs (water). d. Robotics. e. Big data. f. Suborbital communication networks. g. Computational power. h. Inter- and intra-continental facilities – expanded gateways to Antarctica, enhanced landing facilities in Antarctica, and support for distributed science delivery. i. Geophysical techniques. j. Continuity and further technology development in satellite remote sensing of Polar Regions.

HORIZON SCAN CLUSTER 4:

Dynamic Earth – Probing Beneath Antarctic Ice

ARC Workshop Writing Group Participants

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Scientific Questions	*“Reveal Antarctica’s history. Glimpses of the past from rock records collected around the continent’s margins suggest that Antarctica might look markedly different in a warmer world. But rocks from the heart of the continent and the surrounding oceans have been only sparsely probed. Responses of the crust to, and the effects of volcanism and heat from Earth’s interior on, overlying ice are largely undescribed. We know little about the structure of the Antarctic crust and mantle and how it influenced the creation and break-up of super-continents. Ancient landscapes beneath ice reveal the history of interactions between ice and the solid Earth. Geological signatures of past relative sea level will show when and where planetary ice has been gained or lost. We need more ice, rock and sediment records to know whether past climate states are fated to be repeated.”* Kennicutt et al., 2014 *Nature* COMMENT
Highest Priority Technological Advances	
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**
	1. Sensor arrays **1A. Remote sensors/off continent sensors:** not done on site in Antarctica (satellites) Satellite-hyperspectral for example. Resolution limits application **1B. Remotely-deployed sensors** – deployed in Antarctica/Southern Ocean. People do not need to be on site (except for deployment, retrieval, and/or multi-year maintenance cycles). Examples: Geodetic, geophysical (Weather stations, GPS, broadband seismic, magnetic, etc.) **1C. Field surveys** (*airborne, land, marine*) a. Airborne (radar, altimetry, geophysical) b. Field sampling and *in situ* analysis – miniaturization of analytical instruments (application of Mars Rover-style instrumentation) c. In future, could aid in effective sampling, on-site decisions of how much/where to sample. d. Aircraft, helicopters, AUVs (Autonomous underwater vehicles); ROVs (Remotely operated vehicles); UAVs Unmanned aerial vehicles. Payloads. e. Robotics in collection of meteorite sample on ice sheets **Comments on Sensors:** a. Technology developments for sustainable, long-term data transfer sensors b. Standarization of sensors c. Connectivity and interoperability of sensors d. Multi-sensor networks may be required for science, but *will* be required for efficiency of resource use (funds, logistics) **Comments on Resolution/sample rate:** a. Resolution/Defining data requirements – All science to progress in future will require higher resolution b. Given resolution limits 1A-calibrated by 1C required. c. Different dynamic rates (earth vs ice movement, for example), require different resolution of measurements. d. Discrimination based on sample rate required for the science is essential. Volumes of data to be collected, and potentially to be communicated remotely, is a critical starting point to define technologies required. - Full data transfer? - Triggered data transfer? - Data storage? **Comments on environmental impact:** Environmental impact of 1B and 1C always needs to be assessed – high risk, moderate risk, low risk, of environmental impact of technology to be used. **Comments on Power:** Note of emphasis – to achieve *power* goals including a) new power sources and b) new low-power instrumentation, NEEDS: *Technology transfer from existing systems, e.g. as used in space programs.*

What are the highest priority **technological** needs to answer questions in this cluster? (Continued)	**2. Subglacial access/Downhole borehole sensors** (ice, land, marine) for direct measurements – requires drilling and deployment of instruments (short- or long-term). Logging, probes, sensors Into ice, sediment, rock. Image capture/analysis **Comments:** Technology developments: standardization of technology, connectivity and interoperability
	3. Sampling of ice, sediment, rock – drilling to take samples out, including ice coring, and drilling into seafloor and subglacial materials to collect both sediments and bedrock. Notes on required developments: a. Development for clean/greener technologies b. Rapid access drilling technologies c. Drilling technologies (including riser) for improvement of recovery of marine sediments/rocks (both consolidated and unconsolidated glacigenic sediments) d. Development of sea bed drills-flexibility These 2&3 categories cover the list of 2,3,4,5 in the Survey 1 'Top Five' list.
	4. Data Communication Capacity – high volume, long-distance data transfer capabilities for sensor networks, ice, sediment, rock loggers, etc. **Comments:** development for faster, reliable, affordable data communications capability
	5. Power **a. New power sources*:*** efficient (high power density), lightweight, environmentally friendly, capable of operating in extreme cold conditions***.*** Develop alternative energy sources. **b. New Instrumentation** designed for low power consumption, with efficient power management.
	Comments: The top priorities emerging from the surveys were restated but retained and items raised in the White Papers were added. 'Universal' issues (data communications, power) are emphasized. Other topics for prioritization considered but not fully discussed: a. Improved geological models b. Sample analyses technologies
What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	**1. Sensor arrays ("signals")** **a. Remote sensors/ off continent sensors – Satellites** i. Could influence ongoing prioritization for satellites with polar applications. ii. Investigate if 'hosted payloads' – sensors with special polar applications – can be added to payload planned for a satellite that will be launched for another purpose. 'Only' add-on cost required. *10+ years' time frame* **b. Remotely-deployed sensors** – deployed in Antarctica/Southern Ocean. Many remote instruments operational currently; however, development required to achieve sustainable systems for long-term. Cyclical upgrades to take advantage of technological advances (obsolete instruments; lower-power; etc.). i. Interoperability essential to ensure successful multi-sensor networks and international networks: ii. Connectivity: A plug-and-play power and communications system that can be used for a variety of sensors. iii. Standardization – any type of sensor can be plugged in, as science needs evolve. Any nation can contribute to network. Also, *data* should be aligned so can be used by multiple communities. *3-9 years' time frame* **c. Field Surveys** i. Robotics and autonomous vehicles – development required, and dependent on payload requirements, spatial survey requirements ii. Technologies required to deploy remote instruments in special polar environmental conditions – for example aircraft, helicopters, ROVs and UAVs in sea-ice-covered waters. Technologies are required to manage operation of remote instruments – for example, airborne drones. iii. Miniaturization of instrumentation for field-based analyses requires development for cold environment operations. iv. *Strategies* to prioritize operation of remote sensors vs. field-based surveys. Operations managers face 'either/or' choices – funding insufficient to continually add on (for example, airborne geophysics such as IcePod in addition to other modes of airborne surveys or field-camp-based geophysics). Science community needs to prioritize which is preferred mode of data acquisition to meet science requirements.

2. Subglacial access/Downhole borehole sensors – This category includes instrumentation requirements applicable to: subglacial lake environments, ice, rock, marine, and land. Many instruments have been deployed but, again, development required to permit sustainable, reliable, environmentally 'clean', etc, operations. Development requirements are dependent on instrumentation requirements, spatial extent of measurements, etc.

2 year time frame

3. *Sampling of ice, sediment, rock*

a. Ice – ice coring technologies… (no expertise in room /check with ice sheet group in cross-cut discussions)
b. Subglacial bedrock core recovery requires development:

3-9 year time frame

a. Multi-substrate sampling: ice, then sediment, then bedrock sampling, capacity needed.
b. A 'rapid drilling' system required (i.e., development of the RAID system, rotary drill rod systems, wireline rapid drills, etc).

3-9 year time frame

4. Ocean sediments:

a. Improved recovery technologies for ocean drilling required (riser systems).
b. Seabed drilling technologies essential.

2 years

Improved availability of existing technologies (e.g., ANDRILL and IODP) is very important – i.e. science requires more sample records, acquired over shorter time cycles (i.e., not a decade between major core acquisition programs)

5. *Data Communication Capacity* – A major 'step function', as soon as possible, is required to enable the range of science proposed.

Development on many fronts is required:

a. increased bandwidth
b. increased speed
c. reliability
d. affordability

Comments: data can be collected at rates and volumes that can never be transferred by satellite technologies. WHAT needs to be transferred – 'state of health', 'communications to execute project', or actual 'data'? Is there *really* a tight time frame for receiving data, if the analysis is going to take 3 years? Is the data analysis part of a funded project? Or, will the data be collected by one project, but then analyzed by separately funded projects subsequently? Virtual deployments, expanding science community, important. Are there improvements in 'local/regional communication networks' that would improve science projects, science operations? Can there be coordinated transmission of data? Would communications between different operators about operations aid progress of science implementation (for example, King George Island)?

What are the scale factors?

a. Spatial
b. Numbers of instruments (bandwidth)

Issues:

a. Satellites are not in orbits to service communications in Antarctica
b. How do multiple nations share satellites? Are there 'geopolitical issues? Can we support a 'COMNAP satellite'?

Also important to consider investment in data management – for example, data compression, or on-site processing and only transfer 'products' not all raw data

3-9 year time frame

	6. *Power* Development elements required include: a. Affordable b. Greener c. Lighter d. Safer e. Operational low-temperature conditions f. High capacity (high energy density) g. Reliable **a. Power Sources** Develop alternative energy sources *Within 2 years* up to 3-9 year time frame* * requires access to commercial technologies and enhanced cold-environment testing. Mid-size stationary generators are now under development but is still required lighter equipment and advance temperature management and enclosures. **b. Low-power instruments** Important to coordinate between developers, important for engineers to design together with scientists. – *short term, but 3 (not 2) year time frame*
	Comments: Common Issue: technologies exist, but no easy (or any means) for polar science community to access or deploy. Examples: 3D seismic, drilling systems, and data transfer.
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	**1. Sensor arrays ("signals")** a. Remote sensors/ off continent sensors – Satellites – Repeated, any time of the year b. Remotely-deployed sensors – Continuous OR 'any time during the year' c. Field surveys – Austral summer (October-March)
	2. Subglacial access/Downhole borehole sensors a. Multi-substrate sampling / A 'rapid drilling' system required. b. Continuous OR 'any time of the year' c. Ocean sediments: i. Improved recovery technologies for ocean drilling required. ii. Seabed drilling technologies essential. Austral summer (October-March)
	3. Sampling of ice, sediment, rock Austral summer (October-March)
	4. Data Communication Capacity Continuous OR 'any time of the year'
	5. Power – Continuous
	Comment: Continuous is different than 'Any time during the year'
What are the estimated costs to develop/deliver the highest priority **technology** needs? See Survey results for the cost ranges to be used. This is not intended to be a rigorous cost analysis but a general indication of cost to the best of your estimation. If you have no basis for such an estimation please indicate "Don't know", do not guess.	**1A. Sensors 'off continent' – Satellites** $>10,000,000 (25,000,000 – 50,000,000 cost) **1B. Sensor networks – observatories and networks on land or on seafloor:** $1,000,000 – 10,000,000 cost – but this is probably per network, not for an integrated multi-sensor network **1C. Field Surveys**: $1,000,000 – 10,000,000 cost a. Auto-sub: 10million b. IcePod: 3-5 million c. Glider: 0.5 million

	2. Subglacial access (downhole borehole sensors: $500k – 1,000,000 to 1,000,000 – 10,000,000 cost a. temperature probe: <<500k, b. image capture: relatively low cost, c. borehole sensors: mainly relatively low cost?, and d. subglacial lake ROV: 1-10 million
	3. Sampling of ice, sediment, rock: $1,000,000 – 10,000,000 to >10 million cost per project/mission a. Seabed drill (e.g. MeBo): $10 million b. Ship based (IODP): $ 10 million c. Ice shelf based: $10-20 million d. IceCube drill: $25 million e. Rapid Access drill: $~5 million **Comments:** not just purchase cost, but ongoing maintenance costs are commonly the most challenging.
	4. Data Communication Capacity: $500k – 1,000,000 to >10 million cost Satellite for comms: >>10 million
	5. Power – Power sources – $500k – 1,000,000 to 1,000,000 – 10,000,000 cost new battery type: cheap (assuming using off-the-shelf)
	Comments: Considerations on estimated costs: Conceptualize 'support packages' to figure out costs. a. Human, and support chain needed to deploy human, required. b. Technological solution can be substituted. At what point does the investment in B, allow down-sizing to logistical hubs (field camps, stations) with the whole supply chains, which magnifies the cost savings? 'Science' funds vs. 'logistics' vs. 'infrastructure' vs 'technology development' funds – how to actually map all the latter, into the actual science costs?
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	Yes, all questions in the cluster would be addressed
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	a. Power source research efforts will be carried out by commercial interests, national energy departments, etc. Perhaps a consortium of polar programs could commission research on cold-environment-capable energy solutions. b. Planning polar orbit for satellites. Hosting payloads on satellites. c. Low-power instrumentation is of more global interest for science experiments, however, the extreme environment testing is mainly applicable to polar research. d. Drill technologies will need to be developed in collaboration with the commercial drilling sector
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	**Oil industry technologies:** a. 3D seismic b. Drilling: i. Ongoing operations, i.e. not once a decade. Long gaps between projects have meant: 1) a slow progress addressing relevant scientific questions and; 2) that significant technology and capability (especially people) has been lost without adequate training of new capability. ii. Seabed drilling systems **Fiber-optic communications cable to Antarctica** Note; Satellites in polar orbit can download data to Antarctic sites that is then fed to, for example, weather forecasting systems in the northern hemisphere, significantly improving forecast certainties – if these data can be transferred rapidly, for example by fiber-optic cable, could have global impacts – 250 million dollar cost UAV – Unmanned Autonomous Vehicles. Large UAVs, with major long-range spatial capabilities and large payloads, are routinely used outside Antarctica. For example Global Hawk UAV (deployed from off-continent). Nuclear power – future cost-efficient, reliable, environmentally-friendly system developed, then will the political issues allow it to be deployed in Antarctica?

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	The technologies necessary to address the scientific questions in the Dynamic Earth-probing beneath the Antarctic ice´ include: a. Sensor arrays on the continent and in ice/subglacial boreholes; b. Technologies for data and sample collection during field surveys (airborne, autonomous and unmanned and remotely operated vehicles; field sampling, miniaturization, low power requirements, robotics, etc.); c. Drilling systems for the collection and complete recovery of sediment and rock samples from beneath the ice and the ocean. Some of these technologies largely exist, are under development, or require improvements that are achievable in the short-term. Improved availability of existing technologies is key for science advancement, allowing for regular/repeated collection of samples and data. Other needed technologies, such as subglacial bedrock/sediment core recovery or satellite hosted payloads will require 3-9, or more than 10 years to be developed, respectively. Technological developments should aim for the standardization of sensor technology, and the connectivity and interoperability of sensors. This is essential for to ensure successful multi-sensor networks, and to facilitate international collaboration and interdisciplinary science. In addition, multi-sensor networks will also be important for efficiency of resource use (funds, logistics). The questions in this cluster cannot be fully addressed unless large spatial areas, both in the Antarctic continent and the surrounding oceans, are investigated. Some of the questions in the cluster are best addressed in East Antarctica or West Antarctica target regions, though still broad regional areas. The deployment of sensor arrays and increased science activity in Antarctica with the possibility of acquiring continuous or any-time of the year data and the direct communication with the sensor network, will require improvements in the data communication capacity for high volume, long distance data transfer capabilities. All activities described would benefit from power source improvements including, sources for low-consumption instruments, with efficient power management, and new green, efficient and lightweight power sources that can reliably operate in extreme cold polar conditions. All activities conducted in Antarctica and surrounding oceans will have to be environmentally friendly, and benefit from international interdisciplinary collaboration and coordination of science, logistics and infrastructure. The technological requirements for sensor networks, ice borehole drilling and sampling of subglacial sediment and rock cross-cut with needs/requirements in the ` Antarctic ice sheet and sea level´ cluster (geophysical, AUVs, ROVs, etc. Q.24. Q26-32 and subglacial and ocean drilling Q.34). Paleoclimate records of past greenhouse conditions that are recorded in sub-ice and ocean sediments and rocks are also relevant to the`Antarctic atmosphere and global connections´ cluster (Q.8, Q.9), in addition to the geophysical data, sensors and samples that will allow for a better understanding of the distribution and volumes of greenhouse gases stored on the permafrost and clathrates (Q.10). Samples of sediment and rock will also provide information about ecosystem evolution in Earth history (Q. 46).

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**? See Survey results for location descriptions.	**Rank Order (1 is highest priority)**
	1. **On the Antarctic Continent** **Priority – Deep interior of continent** East Antarctic interior is a priority for studying supercontinent evolution, West Antarctica is a priority for studying volcanism and impact on ice sheet. Need is to visit interior rock exposures, deploy sensor networks, conduct airborne and other field surveys, exploration of subglacial environments.
	2. **On or beneath the Antarctic ice sheet** **Priority – Underneath the ice sheet.** To advance understanding of subglacial geology. For example subglacial geology of East Antarctic interior to better understand supercontinent evolution, interior subglacial basins to obtain climate history records.
	3. **In coastal Antarctica including at ice margins** **Priority – Outcrops** at these locations are essential to visit. For example, the West Antarctic coast, particularly around the Amundsen Embayment and Marie Byrd Land, are relatively unknown. Access is available, but limited in time, in geographical access, and commonly tied to available ships.
	4. **In the Southern Ocean / Deep Sea** **Priorities – coastal to deep sea** records to study deep time climate history, ice-ocean interactions, and tectonic evolution of Antarctica/Gondwana. For example the Amundsen Sea, Wilkes Land, Ross Sea, and Scotia Arc are key targets by the marine geology community.
	For this group, large spatial areas need to be investigated to answer the science questions. Some of the questions in the cluster are best addressed in East Antarctica or West Antarctica target regions, though still over broad regional areas. Many are continental-scale questions.

What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	**Example cost access to interior of either West or East Antarctica:** >10 million USD – Example cost estimate field camp providing access to interior West Antarctica: 35 million dollars for WAIS Divide Camp – deployment, several years of ice-core drilling and remote work from camp. Staffing for 2015-16 is 1.1 million, just doing 'clean up' of ice-core drilling camp, and supporting some other science projects. Example cost access to interior East Antarctica: AGAP – U.S. cost approx... 5 million USD/year for 2 years. PLUS funding by other nations, 5-7 million USD for 5 years of POLENET-scale network deployment/operations logistic costs.
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	Yes, all questions in the cluster would be addressed
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access**ed to accomplish the science of this cluster. *Include discussion of specific synergies with other clusters and cross-cutting Horizon Scan questions.*	**Priorities for Access –** To study Dynamic Earth science questions, priority access is to the interior of the Antarctic Continent and, in particular, to the earth underneath the ice sheet. The need is to deploy remote sensor networks, drill and sample sediment and bedrock beneath the ice sheet, explore subglacial environments with sensors and remotely-operated vehicles, and conduct airborne and other field surveys. Accessing records beneath the seafloor is also a top priority, again including drilling and surveying to obtain deep-time records of climate and tectonic history. Many science objectives for *Dynamic Earth* require continental-scale observations. Synoptic observations from sensor networks and integrated drilling/sampling and survey campaigns are needed to reveal patterns of crust and mantle structure, geothermal heat flux, isostatic adjustment and dynamic topography, and rates of geomorphic change. Sectors of the continent and offshore marine realm can be targeted to address specific science questions. For example, networks and surveys over West Antarctica would best serve to investigate the role of volcanism in evolving lithosphere, changing climate and impact on ice sheets, whereas observations in East Antarctica are needed to better understand supercontinent assembly and breakup through Earth history. Marine subglacial basins and the offshore Amundsen Embayment region are key sites of synergistic exploration and sampling for the *Dynamic Earth*, *Ice Sheets and Sea Level*, *Southern Ocean* and *Atmospheres* science clusters. **Priorities for Infrastructure And Logistics –** To succeed in accessing the deep interior of the Antarctic continent, deep-field infrastructure such as shared logistic hubs and transport networks are required. 'Heavy class' icebreakers are required to provide access to coastal stations, the core sites for bringing essential fuel, equipment and personnel to the continent, but also direct access to remote coastal margins and to execute shipborne research in ice-covered Southern Ocean waters.

Highest Priority Infrastructure and Logistics

What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements? See Survey results for descriptions.	**Rank Order (1 is highest priority)**
	1. Shared Logistic Hubs – that can be jointly supported by multiple nations, and offer science opportunities to scientists from many nations. The logistic hubs will entail/support: a. Air transport b. Ground traverse c. Fuel depot(s) These will support work in the deep interior and coastal areas of difficult access, in support of sensor deployments, surveys, drilling/logging and sampling. Such hubs should be capable of scaling, from small- to large-scale. Examine excellence in support elements in each national program and leverage opportunities to adopt these for support of shared logistic hubs. Note: 'fuel is king'! **Direct infrastructure/logistics required for sensor deployments, field surveys in the Antarctic interior and on coastal margins:** a. Requires logistical hubs – typically both stations (delivery materials from off-continent) and deep-field camps. b. Requires appropriate transport modes, for example ski-equipped aircraft and ground traverse capabilities inter- and intracontinental. c. Requires field camp support for field team and transport personnel. d. Requires deployment of fuel – both at logistical hubs and remote fuel caches. e. Requires communications
	2. Icebreakers: a. primary infrastructure for some ship-based activities, such as seismics, high resolution bathymetry mapping and deep-sea drilling in ice covered areas b. can be primary infrastructure for access to coastal research sites c. one element of primary infrastructure for many national stations which, in turn, constitute primary infrastructure for interior stations/logistic hubs Note: *different classes* of icebreakers. 'Heavy' icebreaker (PC1-PC3) required.

	3. Polar Research Vessels: a. Access to coastal sites b. Deploy AUVs, ROVs, sensor networks c. Platforms for coring/drilling, deployment of seabed drilling systems d. Ship capable of launching ROVs/AUVs in ice-infested waters may be needed. e. Survey platform for marine environment
	Comment: Promote access to coastal and/or interior field sites from shared stations, or satellite stations linked with major national bases (i.e., each Treaty nation does not establish a new, small base in a region where many bases are already established). Several of the "new" regions of interest in Antarctica have not been investigated as much as the "easy areas" is both because of access but also other physical constraints such as poor weather. It is not only access but innovation (smarter) in the support for field operations such as drilling that is required in these difficult regions.
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All questions in this cluster.
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	**Shared logistical hubs** – particularly for access to remote regions that requires considerable logistical support such as the deep interior and isolated coastal. Supported by multiple nations who wish to take advantage of logistics available in a region, possibly working together on one project but could be on several different project topics but requiring similar logistics, e.g remote camp, sharing air transport as transport networks, ground traverse, fuel depots etc. Hubs should be capable of scaling from small to large scale. Requires excellent communications between partners on and off continent. Hubs would be temporary, lasting for as long as required for the project/s – for example, one or more seasons, staffed by various teams for longer seasons or year-round activity. Purpose – to deploy sensors, surveys, and drilling/logging/sampling – support all kinds of science. Advantages – better access, shared support not available to some projects/nations/. Shared costs, especially sharing fuel costs. Costs for hubs estimated from $1 – $10 million USD or more, depending on size and location. **Ships – icebreakers and polar research vessels.** a. Icebreakers (polar capacity PC1 to PC3) are primary infrastructure required for some ship-based activities, such as deep-sea drilling and marine research. Also for coastal research sites. Form one element of primary infrastructure for national stations for access. b. Cost: >$5 million USD (depends on class of icebreaker – range needed. c. Polar research vessels with ice capability required for access to coastal sites, to deploy AUVS, ROVS, sensor networks etc. Survey platforms for marine studies. Also used as platforms for marine coring/drilling, and deployment of seabed drilling systems. d. Cost: $500 USD million depending on specifications **Shared facilities/stations for National Programmes** Promote access to science targets via shared facilities at national stations (i.e. Nations planning new infrastructures should consider the advantages of cooperation/coordination with existing stations and logistical support. Infrastructures/logistics above would contribute to multiple science questions, not just one strand of science
Summary and Conclusions	
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Remote sensor networks (on the continent)
	2. Access to the interior of Antarctica
	3. Drilling ice and subglacial/ocean sediment and rocks
	4. Ships/icebreakers
	5. Drilling boreholes and sensors
	6. Shared field infrastructures
	7. Interoperability-multidisciplinary systems
	8. Samples, field surveys
	9. Improved power supplies
	10. Remote sensing satellite (off continent)

HORIZON SCAN CLUSTER 5:
Antarctic Life on the Precipice

ARC Workshop Writing Group Participants

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Scientific Questions	*"Antarctic ecosystems were long thought of as young, simple, species-poor and isolated. In the past decade a different picture has emerged. Some taxa, such as marine worms (polychaetes) and crustaceans (isopods and amphipods) are highly diverse, and connections between species on the continent, neighboring islands and the deep sea are greater than thought. Molecular studies reveal that nematodes, mites, midges and freshwater crustaceans survived past glaciations. To forecast responses to environmental change we need to learn how past events have driven diversifications and extinctions. What are the genomic, molecular and cellular bases of adaptation? How do rates of evolution in the Antarctic compare with elsewhere? Are there irreversible environmental thresholds? And which species respond first?"* *Kennicutt et al., 2014 Nature COMMENT* The questions in this cluster fall into two main areas ((i) what is where and (ii) what is it doing), and that some of the technologies for addressing these two sectors can be very different (but some issues such as access issues, may be similar. The apparent omission of questions relating to Protected Areas (ASPAs) was raised and it was noted that the issues was absent largely because it is a current, and not a 20-year foresight, issue. The sub-Antarctic were considered as part of the larger Antarctic region of interest. However, the COMNAP recognizes 60° degrees South Latitude as the northern delineation of the region of interest. The outputs of the workshop are of value to COMNAP, SCAR and national programs and should therefore not be restrictive. Some national programs make no distinction between the Antarctic and the sub-Antarctic in operational terms while others may only allocate its resources to the geographic scope of the Antarctic Treaty and COMNAP.	
Highest Priority Technological Advances		
At What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Improved sensors, including new sensors, more robust sensors with automated calibration, sensor networks, and higher sensor resolution (system-dependent), for monitoring *in situ* structure (e.g. seal counts) and functional processes and compounds (including contaminants). Sensors are broadly interpreted to include those used sub-glacially to those flying on satellites. The calibration of new robust and long term sensors is needed.	H
	2. Robotic (controlled and autonomous) multi-purpose systems and vehicles for continuous and long-term *in situ* process monitoring and multi-sample recovery and return (including automated retrieval systems for recovering sensing equipment).	H
	3. Better and more integrated platforms for high performance computing, for rapidly growing 'big data' requirements. Such computing underpins modelling, automated image analysis and bioinformatics.	H
	4. High volume automated multi-omic platforms for phylogenetic and functional analysis of multiple large-scale meta-omic sample sets, including automated *in situ* metagenomic analysis and integrated bioinformatics analyses. A multi-omics platform might include automated sample extraction and clean-up, together with parallel NG sequencing of DNA, RNA and protein.	H
	5. High volume satellite/microwave bandwidth for integrating Antarctic data capture and both on-site and off-site analysis	H
	Comments: No substantial variances from survey results are obvious. It is noted that the priorities listed above are generally broader than those listed in the survey, in that they often simultaneously encompass several survey items. Few (if any) research technologies are 'Antarctic-specific', but are applied to an Antarctic location. Considerable overlap with ocean group (bandwidth, sensor technologies, including battery/energy requirements, robotic sampling and analysis). Much of what is considered has substantial implications for energy provision and energy intensity. The ability to efficiently manage 'Big data' is likely to be one of the greatest impediments to the future progress of Antarctic biological research.	

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Sensors – many do not yet exist (at a suitable sensitivity, robustness, in arrays etc). Development ongoing (5 – 10 years?). Some may be Antarctic-specific.
	2. Robotic platforms – exist for marine systems but not for terrestrial systems. Different timescale for the two systems. For the former, need further development (5 years), especially for retrieval operations; for the latter, 5 – 15 years (except UAVs, which are relatively advanced). Some terrestrial robotic systems do exist (which address other questions (such as access) – relevant to safety of traverses).
	3. Larger and faster computational platforms for 'big data' analysis. Under development, with continuous evolution. More a cost and availability issue.
	4. Multi-omic platforms ((e.g. for genomic, transcriptomic, metabolomic etc. research) and associated software. Under development by big international companies, but 5 – 10 years to implementation.
	5. Enhanced bandwidth for big data transfer. Microwave/optical fiber/satellite support: Many new technologies are under development; current – 10 years
At what temporal scales will these **technologies** most likely be used and how frequently?	1. Sensors – all temporal scales (from continuous to intermittent)
	2. Robotic platforms – all temporal scales (from continuous to intermittent)
	3. Computational platforms – continuous
	4. Multi-omic platforms – intermittent. Will vary from group to group. Multi-use platforms are feasible.
	5. Enhanced bandwidth – continuous
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Impossible to estimate specifically (from tens of thousands to multi-millions) depending on type of sensor and the objective (e.g., sub-glacial lake sensors are under development; but others will be developed globally)
	2. Highly variable. E.g., UAV development costs are low, c.f., very high (see cost of development of Mars Rovers)
	3. Computational platforms – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue.
	4. Multi-omic platforms – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue. The greatest cost to the user is the training (particularly of bioinformatics researchers).
	5. Developments are undertaken by large communications organizations. For Antarctic researchers, this is a user cost, not a development cost, issue. COMNAP has an important role in coordination and information exchange within and between national Antarctic programs. Developments led by Arctic communities.
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/ which questions (by Horizon Scan number)?	All of these technologies support multiple scientific questions. a. For Sensors: Q43, 45, 47, 49, 50 – 53, 60 – 63, 65 b. For Robotic platforms: 43, 44, 48, 49, 50, 51, 54, 57, 58, 60, 62, 63, 65 c. For Computational platforms: 43-46, 49, 53-55, 57, 59, 60, 62, 64-68 For multi-omic platforms: 43-45, 47, 52-58, 64, 67, 68 For high band-width communications: all questions
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	a. All the biggest technological challenges are beyond the control (i.e., independent design and construction) of the National Antarctic programs, in that these are generic challenges applicable to research which extends to systems far beyond the Antarctic sphere. Few of these challenges are likely to be developed solely for the Antarctic (for example, terrestrial robotic platforms can be used in other extreme environments – polar, alpine, desert, etc.). b. Adaptations of existing technologies may be the most efficient method for designing Antarctic-specific platforms c. By comparison, these are not beyond the 'capability' (use) of National Antarctic programs – i.e., they will be used by such programs. d. For computational platforms, these technologies are well within the capabilities and control of the National Antarctic programs. e. For multi-omic platforms (i.e., for genomic, transcriptomic, metabolomic research), the same applies. However, the capability issues for in situ platforms (requiring support from companies and agreements between national programs). It was noted that the technology developments may change personnel balances (more technicians). f. For high speed/volume communication systems, these are completely within the capabilities/ control of national Antarctic programs.

Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Antarctic researchers are usually cognizant of new technologies as they arise, and constraints may be more related to the availability of funds than lack of awareness. Some very innovative and relevant technologies may not yet be publically available (i.e., those that are developed initially for military purposes). There technological developments that might exploit Crowd Sourcing approaches using cell phones in Antarctic monitoring and surveillance.
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	Life on the Precipice covers environments from the subglacial to the marine, to terrestrial systems, and spans as wide a range of organisms, from bacteria to marine mammals, and encompasses a wide variety of themes in biology and ecology. Given this diversity the key technologies required are sensors for both structural (species detection) and functional (e.g. nutrients, CO_2) purposes to be used in environments from subglacial to marine, and including sensors for use on satellites to UAVs. Recognizing that field personnel will always be a key part of any program, much of the work required to address these new questions will require automated sampling and robotics. The Omic approaches (e.g. genomic, transcriptomic, metabolomic) will form a key part of this work. In situ omic platforms which allow real-time analysis and onward transmission of data (rather than samples) will require deployment across a range of sites, keeping up with developments globally. Modelling, bioinformatics, ecoinformatics and associated approaches will require increasing access to high performance computing. Accessibility of such computing, both in the Antarctic and at home institutions is essential. High speed communication via satellite, microwave and other technologies will be a significant technological requirement to deliver the science for Life on the Precipice. Such communication includes capabilities from ships given their ongoing significance for deep sea work and the requirements for integration of data from AUVs, gliders and equivalent instrumentation. The issue of technology scanning (by Antarctic researchers) should be on-going and proactive, so as to take advantage of the latest and most sophisticated technology. COMNAP should establish a scanning group to look for new technologies relevant to their remit (with respect to energy, science, and communication). Many questions will be more readily answered if SCAR promotes a high level of integration between relevant organizations. COMNAP and SCAR should ensure that mechanisms for transfer of knowledge and exchange of personnel are available.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of **access**?	**Rank Order (1 is highest priority)** 1. Coastal regions of terrestrial Antarctica and the sub-Antarctic islands 2. Access from the ocean to the land (including ice-breakers, sea-ice transport technologies, air transport) 3. Deep sea access (including vessel capability, remote vehicles) 4. Development of 'transitory' (modular, mobile) facilities for temporary support of research activities 5. Extended temporal access (through winter) to Antarctic sites (note cross link to remote technologies) **Comments:** a. It was argued that the most important biological questions can be mostly addressed by access to areas where research is already undertaken (existing bases etc.). b. It was also argued that the most important element of access is often not physical, but is actually access to data (i.e., increased data-sharing). c. The group suggests that a discussion with the marine community on aspects of access, including deep marine access, is necessary d. The group notes that Q55 required access to all regions of the Antarctic continent, the southern oceans and the sub-Antarctic islands
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Coastal regions (existing sites and locations) 2. Access from the ocean to the land 3. Deep sea access 4. Development of 'transitory' facilities 5. Extended temporal access **Comments:** The costs range is huge for each of the items: it will range from project grant cost levels (thousands) to, for example, joint cooperation for design and construction of new vessels (multi-millions). In some cases, costs can be reduced by a greater degree of coordination between national Antarctic programs, including the sharing of station facilities. The concept of a regionally based 'fleet coordination' approach for oceanography and base support would be highly beneficial.
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)	Yes. As this covers temporal and special data issues, all questions are relevant.

Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access**ed to accomplish the science of this cluster.	Much of the access to Antarctic habitats, particularly terrestrial habitats, required to answer the Horizon Scan questions, does not require vastly extended logistics to support access to remote sites. Much of the research required to answer most of the questions posed can be done at sites which are currently intensively studied. That said, there is a clear need for expansion of current studies from two dimensions to four – expanding to increase the physical depth of analyses and to cover a much wider temporal range, currently mostly restricted to a relatively short summer season. The requirement to increase the understanding of the range and diversity of Antarctic terrestrial biota does, however, also require access to remote areas and to specific habitats (such as intra- and sub-glacial ice habitats). Some of this need could be serviced by the development and use of mobile modular (transitory) facilities. Access to marine habitats has more substantial access requirements, but overlaps very substantially with the requirements of the physical sciences researchers (oceanographic, glaciological, and geological). Many of the Horizon Scan questions require comprehensive access to all areas of the circum-continental oceans, including many which are currently poorly accessed (sub-sea ice, sub-glacial and ice-shelf, deep marine) and a substantial extension the temporal access (from seasonal to year-round). The most dominant theme of the discussions was a complete consensus on the enormous benefits of science-driven collaboration. Such collaborations offer a very wide range of 'access' advantages, including access to field sites, technologies, skills and resources and, above all, data. The group concurred that the benefits of data sharing between researchers across all national platforms provides an effective mechanisms for promoting Antarctic research across all subject areas.

Highest Priority Infrastructure and Logistics

What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)**
	1. Improvement of modularity in facilities (mobile, collaborative).
	2. Coordination of existing ship and marine logistic operations.
	3. Upgrade and enhancement of power delivery (in a renewable manner).
	4. Improved cleaning technologies for Antarctic research and support operations in both marine and terrestrial environments to reduce contamination, transfer of biological materials etc.
What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. High cost (sub-millions)
	2. Low cost (but high organizational burden)
	3. New technology required – cost estimates difficult
	4. New technology required – costs probably not excessively high.
If available, will these infrastructure and **logistical needs support multiple** scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	In general, the proposed infrastructure and logistical elements would support, in one way or another, all the questions in the cluster. For example, the development of mobile and modular facilities can potentially be used for research addressing virtually any of the questions listed under the Life on a Precipice heading.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster *n Scan questions.*	Reliable access to terrestrial, freshwater and marine environments by researchers is a key requirement for delivery of Life on the Precipice. While automated sampling and robotic sampling will require development to extend reach both through time and across space, the presence of personnel in the field, extending across full years, will remain essential. Indeed this need will grow as understanding of the full season grows in significance. Access to all areas is required, though coastal regions remain a priority for terrestrial work. Improved deep sea access is clearly essential. Marine infrastructure to provide access to ocean areas from shallow sites, especially those that are hardly accessible under the permanent sea-ice and ice shelves the deep sea on an ongoing basis requires consideration. The development of modular facilities both for terrestrial and marine work is an essential component of new infrastructure development. Such modular facilities will enable access to new areas for longer periods without the need for expensive permanent infrastructure. Addressing the questions will require increasing power at a range of both station sites and remote localities. Such power delivery in a renewable way will be a key logistic/infrastructure need. An increasing focus on green technologies will be essential to deliver the science with minimal environmental compromise. Ensuring that transfer of material or propagules among sites, which would compromise the environment and the ability to understand evolutionary processes, will not happen is essential. This will require new developments in the provision of clean gear or cleaning technologies, at the scale of individuals to ships, aircraft and vehicles. Many of the infrastructure requirements can be substantially addressed by improved collaboration and strategic sharing of resources. This might include sharing of station facilities, joint planning and coordination of regional shipping to address simultaneously logistic and research needs, and shared air operational discussions. Access needs to high performance computing and multi-'omics' platform infrastructure can be addressed through personnel exchange, science-driven collaboration, and joint planning of research. Many of the issues raised above relate to access processes, often to remote and difficult areas, and collaboration between programs is likely to be a key element of addressing infrastructure needs.

Summary and Conclusions

What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Enhanced collaboration, including improved data sharing and access to stations, logistics and operational activities is a critical requirement for future Antarctic research (see Article III of the Antarctic Treaty)
	2. It is important to balance the differential skills, capabilities and capacities across different national platforms, particularly in the fast-developing and technology-intensive research sectors, through better resourcing of researcher exchange programs (and capacity building) via multiple mechanisms including scientific collaborations.
	3. New technologies for autonomous and robotic sample and data recovery, in order to expand sample acquisition over both much wider spatial and temporal scales, is a high priority.
	4. Acknowledging that autonomous systems will not always is sufficient for data and sample acquisition, guaranteed access for scientific personnel to a wider Antarctic area, and extension of that access to encompass much wider temporal scales, is a priority.
	5. Many of the anticipated advances in technology (whether diagnostic, surveillance, diversity research or ecological function) will result in very large datasets. The need for access to much greater computational power and speed, will be critical for future Antarctic research.
	6. There is value in coordination and collaboration between different disciplines. Infrastructure and logistics designed for one objective (e.g., sub-sea ice marine water surveys) will be appropriate for other objectives (e.g., biological surveys).
	7. Investments into the development of new sensors and sensor technologies are considered to be a very high priority.
	8. The development of new technologies should aim to minimize environmental impacts, including the minimization of human impacts.
	9. Data generation in Antarctic research will increase dramatically and it will be critical to increase bandwidth and communication capacities within and from Antarctica.
	10. Joint work in key research areas involving large collaborative projects. Many of these questions require joint collaboration on infrastructure, access and logistics that is science driven.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	The dramatic developments in the 'omic' technologies have the capacity to transform Antarctic biological research over the next 1-2 decades. The opportunities for collaboration (sharing of research objectives, infrastructure, field program, data analysis etc), if supported and managed effectively, could have an equally dramatic effect on future Antarctic research.

HORIZON SCAN CLUSTER 6:

Near-Earth Space and Beyond

ARC Workshop Writing Group Participants

Co-leads: John Storey & Allan T. Weatherwax
This Writing Group report was not written at the workshop. The report was written on behalf of representatives from the SCAR Astronomy and Astrophysics from Antarctica Scientific Research Program and from the Sun Earth Relations community of SCAR.

Scientific Questions	*"The dry, cold and stable Antarctic atmosphere creates some of the best conditions on Earth for observing space. Lakes beneath Antarctic glaciers mimic conditions on Jupiter and Saturn's icy moons, and meteorites collected on the continent reveal how the Solar System formed and inform astrobiology. We have limited understanding of high- energy particles from solar flares that are funneled to the poles along the Earth's magnetic field lines. What is the risk of solar events disrupting global communications and power systems? Can we prepare for them and are they predictable?"* Kennicutt et al., 2014 *Nature* COMMENT Life in the Universe: One key question overlooked in the Horizon Scan is whether or not life exists elsewhere in the Universe. Although touched on peripherally by Question 47: ("How do subglacial systems inform models for the development of life on Earth and elsewhere?"), it is a crucial question in its own right; one that should be answerable within the next three decades. Investigating what form that life takes, and how it has evolved separately from life on Earth, is one of the most exciting endeavors for the future. Space Weather and Climate Change: Question 72 states "How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere?" This question, together with Q47 above, should receive further attention. Changes occurring in interplanetary space have a profound effect on the upper atmosphere, especially at the poles. One needs to understand the physics linking the space environment to that of Antarctica, and how this subsequently influences the global atmosphere. Effects associated with solar variability, perhaps through auroral precipitation, are thought to perhaps impact climate change.	
Highest Priority Technological Advances		
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. High bandwidth networks on/off continent and continual data transfers in real time from locations throughout the Antarctic.	H
	2. Energy efficient high-performance computing hardware and advanced data analysis techniques.	H
	3. Remote/robotic observatories optimally and strategically deployed across the plateau.	H
	Comments: Overall, pressing technological issues that must be resolved in order to address the science goals include: • Energy efficient high performance computing hardware. • Large data storage devices able to withstand the low atmospheric pressure on the high plateau, and possible cold-soaking (extreme conditions). • Low power consumption cryo-coolers capable of maintaining instruments at 4K and below. • Renewable energy technology such as wind turbines able to operate efficiently on the high plateau, with low wind-speeds, low atmospheric pressures, and very low temperatures. • Development of a diesel power pack at the tens of kW level that has low particulate emission, and can operate unattended for 1 to 2 years.	
What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	These technologies listed above are all in a state of continuous development. They are available in some form or another at present. There is no "end point". See the Autonomous Polar Observing Systems (APOS) workshop report for further details.	

At what temporal scales will these **technologies** most likely be used and how frequently?	1. continuous	
	2. continuous	
	3. continuous	
	Comments: These technologies are all in a state of continuous development. They are available in some form or another now, and are currently being used. There is no "end point".	
What are the estimated costs to develop/deliver the highest priority **technology** needs?	These technologies are all in a state of continuous dvelopment, there is no "final cost", but rather an ongoing development cost. The overall cost is of the order of a 1-10 millions of dollars per year.	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	These technologies are important for all of the questions listed including 69-73 and Q47. Recent advances in critical engineering and logistic support will help continue to facilitate the objectives in this cluster.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Both the energy efficient high-performance computing hardware and the high bandwidth networks are under development for other purposes in industry and science. In addition, specific technologies are under development for astronomical purposes alone, such as the development of novel interferometric telescopes. However, for the most part, it is technological advances for broader purposes that are adopted by astronomers and space scientists for their needs.	
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	There are no obvious technological capabilities currently available that are not being employed or considered for use in Antarctica	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	There is a clear trade-off between communications bandwidth and capability for on-site data processing. The former is dependent on the infrastructure provided by the national programs, the latter requires either significant advances in energy efficient high-performance computing hardware and/or the availability of more electrical power. To fully answer the questions related to the Dark Universe and extra-terrestrial life requires the deployment of optical/infrared telescopes. A key issue is that the science drives us towards a telescope that is too large to deploy until the engineering risks have been retired through a series of pathfinder experiments. Identifying funding sources for such pathfinders is a critical challenge. Large single-dish telescopes will require novel telescope designs (e.g., segmented mirrors), in order to be transportable to remote locations. Technologies to facilitate this might include off-axis mirrors, lightweight (carbon fiber) mirrors, and high precision inertial pointing systems. Research in the polar regions also supports the high-latitude observations needed to understand fundamental aspects of coupling between the solar wind and Earth's atmosphere, ionosphere, and magnetosphere. The vast geographical regions in both hemispheres provide access to a broad range of geophysical phenomena, spanning magnetic and geographic latitudes from the sub-auroral zone to the polar caps, at altitudes from the troposphere to near-Earth space. While the northern hemisphere is relatively well Instrumented with regards to near Earth space observations, the southern polar region is not, primarily because of the extreme Antarctic climate and the lack of manned facilities with infrastructure. The situation in the southern hemisphere, however, is changing with the development of technologies that support autonomous measurement systems that can be deployed in remote locations and operate unattended for long periods of time in severe environments.	

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. South Pole station	M
	2. Balloon platforms	M
	3. High plateau sites remote and permanent stations.	M
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	The overall costs are not known. However, development is underway by several SCAR countries on each item listed.	
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	For Eyes in the Sky and near Earth space observations, all three areas are important for all three of the questions.	

Highest Priority Infrastructure and Logistics

What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Wide bandwidth, continuous communications infrastructure	
	2. Air access to high plateau.	
	3. Power generation capability of tens of kW at remote sites	

What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	Responses are predicated on the assumption that there will be continued support, at least the current level, of South Pole and McMurdo infrastructure, including the continued development of long duration ballooning. There is also concern about the long-term availability of the large quantities of helium needed for balloon platforms.
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All three infrastructure/logistics areas are important.
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	The greatest challenges to be faced are the ever-growing energy requirements and the need for greatly increased data transfer rates. For example, future neutrino experiments at South Pole are anticipated to need off-continent data transfer of 1000 GB/day (compared to 150 today), while 24-hour coverage will be important for future Cosmic Microwave Background experiments. **South Pole station** Electrical power and data-transfer rates are key challenges. As extended neutrino detector arrays are deployed, delivering hundreds of watts of power to the array stations up to 10 km away remains problematic. As detectors grow to occupy areas of up to 1000km2, autonomous power systems may provide the only solution. **High plateau sites** Future logistic support of experiments on the high plateau might be done in a number of (non-exclusive) ways. Existing stations (Domes A, C, and F) can further develop their support capabilities, autonomous field observatories such as Ridge A might continue to grow as fully-fledged robotic stations, and one or more new high-plateau sites could be opened up.

Workshop Goal #4 – Summary and Conclusions

What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Logistical access to the Antarctic Plateau (e.g., flights).
	2. Technological access to the Antarctic Plateau (e.g., remote/robotic observatories).
	3. Real-time data access across Antarctica is critical.
	4. Wide bandwidth, continuous communications infrastructure.
	5. Continued support for Long Duration Balloon flights.
	6. South Pole and other manned stations need infrastructure upgrades to power and data systems.
Comments	Input to this report comes from the responses to the two ARC/COMNAP surveys, plus a white paper on the technological challenges and logistical needs of the Antarctic astronomy and astrophysics community that resulted from a dedication discussion held amongst 40 members of the SCAR AAA community on 10 August 2015. Further input was obtained from the report entitled Solar-Terrestrial Research in Polar Regions: Past, Present, and Future National Science Foundation grant PLR-1258007] and the report from the Autonomous Polar Observing Systems (APOS) workshop, held at the Bolger Center in Potomac, Maryland on September 30- October 1, 2010. The Sun Earth Relations community of SCAR via the action group SERAnt also provided valuable input.

HORIZON SCAN CLUSTER 7:
Human Presence in Antarctica

ARC Workshop Writing Group Participants

Co-leads: Steven L. Chown & Yves Frenot

Rodrigo Mousalle Bueno, César A. Cárdenas, Don A. Cowan (Scribe), Gen Hashida, Marcelo Leppe, Daniela Liggett, Javier Negrete, Hyoung Chul Shin, Mario Proaño Silva, Sonia Ramos-Garcia, José Augusto Viera Da Unha De Menezes, Veronica Vlasich

<table>
<tr><td>Scientific Questions</td><td><i>“Forecasts of human activities and their impacts on the region are required for effective Antarctic governance and regulation. Natural and human impacts must be disentangled. How effective are current regulations in controlling access? How do global policies affect people’s motivations to visit the region? How will humans and pathogens affect and adapt to Antarctic environments? What is the current and potential value of Antarctic ecosystem services and how can they be preserved?” Kennicutt et al., 2014 Nature COMMENT</i>
• It is noted that the survey results show a sampling bias, given that relatively few social scientists were respondents (although probably reflecting the proportion of social scientists in the larger Antarctic research community) resulting in a very marked focus on technological emphasis (as was the intention of the survey).
• Responses 1-3 below are aligned with answers to Life on a Precipice.
• It is recommended that COMNAP continue to address the issue of global data sharing from publically funded research.
• Most questions in the Human Presence cluster require improved access to data (including archival material), but not all of them require specific technology (other than commonly available data storage and database capacity, high-speed internet connection and certain software used for data analysis, e.g. NVivo and ArcGIS).
• While this report focuses on those questions that have specific technological requirements, this is not meant to undermine the importance of questions (e.g. around governance and regulation) without particular technological requirements.
• The White Paper submitted to the ARC Workshop by the SCAR Humanities & Social Sciences and History Expert Groups contains details on specific structural and methodological peculiarities and requirements of social sciences and humanities research in relation to the SCAR Horizon Scan questions.</td></tr>
<tr><td colspan="2">Highest Priority Technological Advances</td></tr>
<tr><td rowspan="7">What are the highest priority technological needs to answer questions in this cluster?</td><td>Rank Order (1 is highest priority)</td></tr>
<tr><td>1. Advanced data analysis techniques (HP computing) and improved bandwidth</td></tr>
<tr><td>2. Improved ecosystem models</td></tr>
<tr><td>3. New and better sampling and handling technologies</td></tr>
<tr><td>4. Better sensing and surveillance technologies and tracking systems, including autonomous tracking devices and smart technologies (e.g., for vessels, for landings, for land vehicles, for scientific expeditions and other land-based human activities such as camp sites)</td></tr>
<tr><td>5. Imaging and recording equipment suitable for use in extreme climate conditions</td></tr>
<tr><td>Comments:
Responses 1-3 above align with Life on a Precipice. For item 4, some of these data exist, but coordination of data capture and storage, and the sharing of data, are both poorly organized. To thoroughly respond to the Horizon Scan questions in the “Human Presence” cluster developments outside the Antarctic domain influence the context (or even determine the questions) and are a significant influence. Social scientists’ and humanities scholars’ attention to ‘Antarctica’ includes activities beyond Antarctica. The technological requirements for data collection and analysis described need to reach beyond the Antarctic realm.</td></tr>
</table>

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Advanced data analysis techniques (HP computing) – larger and faster computational platforms for 'big data' analysis. Under development, with continuous evolution. More a cost and availability issue.
	2. Improved ecosystem models – actually dependent on computational capacity (see above).
	3. Sampling and handling technologies: For example, robotic platforms exist for marine systems but not for terrestrial systems. Different timescale for the two systems. For the former, need further development (5 years), especially for retrieval operations; for the latter, 5 – 15 years (except UAVs, which are relatively advanced). Some terrestrial robotic systems do exist (which address other questions – such as access).
	4. Better sensing and surveillance technologies and tracking systems – the technology mostly already exists, so this is an issue of implementation and sharing of the resulting data.
	5. Imaging and recording equipment suitable for use in extreme climate conditions – already widely available (some adaptations may be required)
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	1. Advanced data analysis techniques (HP computing) – continuous
	2. Improved ecosystem models – see above
	3. Sampling and handling technologies – intermittent to continuous (depending on the nature of the sampling objectives and technologies)
	4. Better sensing and surveillance technologies and tracking systems – usage is continuous
	5. Imaging and recording equipment suitable for use in extreme climate conditions – usage depends on the nature of the research objectives and imaging/recording technologies
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Advanced data analysis techniques (HP computing) – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue.
	2. Improved ecosystem models – impossible to estimate (other than a requirement for larger computational capacity) – probably a human resource issue
	3. Sampling and handling technologies – Highly variable with respect to autonomous sapling platforms. E.g., UAV development costs are low, c.f., very high (see cost of development of Mars Rovers)
	4. Better sensing and surveillance technologies and tracking systems – relatively low cost technology
	5. Imaging and recording equipment suitable for use in extreme climate conditions – relatively low cost technology
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	1. Advanced data analysis: Q74, 75, 79, 80
	2. Improved ecosystem models: Q74, 75, 79, 80
	3. Improved sampling and handling technologies: Q74, 75, 79, 80
	4. Better sensing and surveillance technologies and tracking systems: Q74, 75, 78
	5. Imaging and recording equipment: Q75, 76, 78
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	All the biggest technological challenges are beyond the control (i.e., independent design and construction) of the National Antarctic Programs as these are generic challenges applicable to research which extends to systems far beyond the Antarctic sphere. Few of these challenges are likely to be developed solely for the Antarctic (for example, terrestrial robotic platforms can be used in other extreme environments – polar, alpine, desert, etc). Adaptations of existing technologies may be the most efficient method for designing Antarctic-specific platforms. However, the implementation of surveillance and tracking technologies and processes is completely within the capabilities/control of National Antarctic Programs.
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Antarctic researchers are cognizant of new technologies and constraints may be more related to the availability of funds than lack of awareness. Some innovative and relevant technologies may not yet be publically available (i.e., those that are developed initially for military purposes). Surveillance and tracking technologies widely used elsewhere could be rapidly and readily translated to the Antarctic (where they currently do not exist). Imaging and recording equipment is widely used and relatively readily available but may have to be adapted to be suited for use in Antarctica's extreme conditions.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster. *Include discussion of specific synergies with other clusters and cross-cutting Horizon Scan questions.*	Human Presence encompasses a diverse set of questions that integrate the life sciences and a range of social sciences and humanities disciplines, including anthropology, economics, history, human geography, law, political sciences, and social psychology. The integration of methods of inquiry from such a wide range of disciplines requires (a) the availability of suitable technologies, and (b) the reduction of barriers to access to materials, actors and systems that go beyond technological requirements. The technologies required to address the Human Presence questions are similar to those for Life on the Precipice. High performance computing for advanced modelling both in the life and social sciences is a key requirement. Better sensors, and more broad deployment, both in space and time, of such sensors, including robotic and automated sampling, will be required to understand impacts. For example, understanding new contaminants, the arrival of new species, and the impacts of both requires such sampling. In marine systems, automated systems for understanding fishing impacts will be essential, coupled with information on the scope and extent of such resource extraction. Sensing, surveillance and tracking systems to provide information on movements of vehicles of all kinds, and to understand volume of visitor access to various sites require deployment and in some cases development. At the same time, it is worth noting that attention should also be paid to technologies that would assist in mapping and assessing existing material legacies (e.g. building remains or artefacts) in the Antarctic in a coherent and systematic manner. While improved sensing and robotics technologies are essential to address the environmental science aspects of questions in the Human Presence cluster, there is also a pressing need to overcome barriers to data access. To effectively address the questions related to human impacts and governance, detailed information about human activities in the Antarctic – from science operations to tourism to fishing and other commercial activities – that is recorded by the operators or facilitators of human activities in Antarctica needs to be accessible. In conclusion, for many of the more humanities and social science focused questions, the key technological constraints are small. However, access to the continent for social scientists and humanities researchers as well as access to information and improvement of this access are significant. An element of this access goes to the need to improve understanding of the need for use of privileged information. The humanities and social sciences have well-developed codes of practice for the use of such information. Importantly, little progress will be made on several of the key questions without better general appreciation of the need for the collection and provision of such data – even if the latter are through very specific contractual agreements.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**? See Survey results for location descriptions.	**Rank Order (1 is highest priority)**
	1. Coastal regions of terrestrial Antarctica and the sub-Antarctic islands, particularly high 'intensity' sites (research and tourist)
	2. Remote ice-free areas of the continent
	3. Access to the maritime domain with ships
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Cost estimates are relatively low (for access issues) because the sites identified are those which are already heavily supported by national logistics and related research activities
	2. Logistic costs are high (given the complexity of logistics support)
	3. Cost estimates are relatively low as maritime areas are readily and regularly accessed by ship (cruise ships, research vessels, fishing vessels)
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	All questions (possibly excepting Q76), are relevant to all priorities.
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access**ed to accomplish the science of this cluster.	a. Understanding anthropogenic change relative to other change may require access both to current and new remote sites. Much of the access needs for this question can be met through current arrangements, though these may change as the spatial and temporal extent of science and tourism in the region changes through time. The requirements are essentially of an interactive form, where changes in some areas will be required to meet changing research and access approaches. b. Ongoing access by social science and humanity researchers to field sites is essential. Much of this will require consideration in planning such work in coordination with other activities. c. Access to high impact sites and to new sites will be required to understand the ways in which changing patterns of activity are impacting the environment and how successful various arrangements are in addressing these impacts. d. Access to the maritime domain is essential as the highest volume of people access Antarctica by sea. Whether investigating biophysical or social sciences facets of research, tourism or marine harvesting activities, access to the maritime domain is critical. e. For deep sea impacts a range of autonomous vehicles as well as ship capability will continue to be required. Near-shore and benthic access across a range of areas remains essential.

Highest Priority Infrastructure and Logistics

What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)** 1. More collaboration between national Antarctic programs, including logistics sharing. 2. Equal opportunity for social sciences and humanities scholars to Antarctic field programs. 3. Improved coordination of data collection, data storage and access to information.
What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Costs may be relatively low, as collaborative activities may be 'buried' within national Antarctic program budgets 2. No additional costs are anticipated, as this element is embedded in existing programs
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	Relevant to all questions
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	A key infrastructure and logistic requirement to answer questions included in Human Presence in Antarctic is science-driven collaboration. This includes collaboration and cooperation among states, among stations, among disciplines. It also includes collaboration with humanities scholars and social scientists working in the Arctic and sub-Arctic, where understanding human presence is arguably more established. Access to information and to sites will be essential, along with development of logistics to ensure that best use is made of opportunities that emerge from the full range of science and logistic activities.

Summary and Conclusions

What are the top "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Increased investment in survey capabilities/tracking (of human and vehicle activities, propagule transport, establishment, survival, contamination, etc) relating to anthropogenic impacts is important 2. Enhanced collaboration, including improved data access and sharing, is a critical requirement for future Antarctic research (see Article 3 of the Antarctic Treaty) 3. Researcher exchange programs (which includes a trans-polar exchange of researchers) are essential for delivering the research in this cluster. 4. Greater access for researchers to other researchers, stations, logistics and operational activities and Antarctic programs, across national boundaries, is essential 5. Enhanced sharing of technology is critical, especially in consideration of the fact that in some countries access to high-speed internet or data storage is not commonly available. 6. The research insight benefits from equal opportunities access by for the social scientists and humanities researchers to the continent to gain access to the continent (removing barriers to access and enhancing capacity building). 7. Considering that the Antarctic humanities and social sciences are still at a capacity-building stage, they are in need of more opportunities to collaborate, more national and institutional acknowledgement of their contributions to empirical understandings of the human presence in Antarctica and more funding opportunities specific to the methodological approaches taken by humanities scholars and social scientists. 8. Researchers from the humanities and social sciences should be afforded equal opportunity of access to Antarctic field programs.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	New diagnostic technologies, including 'omics' technologies, will have a dramatic effect on our ability to detect, monitor and predict the effects of human activities on and around Antarctica.

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