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Dear Dr O’Connell

Re: Revision of the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21

Thank you for the opportunity to provide input into the revision of the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21. The enclosed submission from the Australian Academy of Science has been coordinated and prepared by its National Committee for Antarctic Research, which represents the physical and biological sciences relevant to studies of and from Antarctica and the Southern Ocean. In preparing this response, the committee consulted with other National Committees that covers fields of science relevant to the Strategic Plan. It has been endorsed by the Executive Committee of the Academy. I am pleased to present this submission to the Council.

Should you require any more information or wish to discuss the submission in further detail, please contact the committee chair, Professor Steven Chown, via our office (nc@science.org.au; 02 6201 9400) or directly (steven.chown@monash.edu).

Yours sincerely

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Submission to the Australian Antarctic Science Council's Request for Advice on Revision of the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21

Executive Summary

The Australian Academy of Science welcomes the invitation to contribute advice to the Australian Antarctic Science Council in response to its request concerning the *Revision of the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21* (***AASSP***). The Academy has consulted widely, with this submission reflecting the outcomes of that consultation. The Academy recognizes that the majority of the Themes identified in the original ***AASSP*** remain relevant to Australian Antarctic Science today. Substantial revisions are required, however, to take into account new scientific developments and changes in national strategy, capability and resourcing. Proposals for and justifications of revisions to the ***AASSP*** content are set out here. These include recognition of the need for at least two related themes in the climate processes and change area, a rearrangement of the ecological sciences and biodiversity themes to remove separation of work in the marine realm, and the addition of fields to reflect capability in Geodesy, Geophysics and Mapping, and in Astronomy, Radio Science and Space Science. The Academy strongly supports retention of a 'Frontier Science' theme, but renamed to reflect the reality that frontier science is produced across all of the areas. In addition to a specific recommendation concerning consideration of these content-based proposals, the Academy makes nine other recommendations which concern arrangements and support for the science, which will considerably enhance the ability of Australia to deliver its aspirations articulated in the *Australian Antarctic Strategy and 20 Year Action Plan*.

Recommendations

1. Despite the availability of the ASCI and SRIEAS funding, the Australian Antarctic Science grants program be continued, with increases matching the rising costs of research consumables and personnel, and preferably enlarged to meet the Australian capability in Antarctic research reflected through interest in the Special Research Initiative in Excellence in Antarctic Science call made by the Australian Research Council.

2. In revision of the ***AASSP*** close attention be given to how global leadership in Antarctic science will be maintained by Australia with significantly reduced access to the continent, sub-Antarctic and Southern Ocean, especially over the next five years. One potential solution is collaborative arrangements with other nations that cover whole of program interests.

3. In further development of the ***AASSP***, and in particular the specifics of research to be undertaken within each thematic area (known as Streams in the previous ***AASSP***), broader consultation over a longer time span, including 'town hall' meetings in key locations, be undertaken.

4. Theme and Stream leaders (or their equivalents under a revised ***AASSP***) be sought from across the Australian Antarctic science community through an open process coordinated by the AASC, which then advises the Department of the Environment and Energy or its delegate.

5. Broad developments across the Australian research landscape be considered as part of the development and implementation of a revised ***AASSP***.

6. The revised ***AASSP*** be reduced in length such that it focuses on the significance of Antarctic science globally and the role Australia can play, highlights key strengths and opportunities for Australia as well as constraints and how they are to be managed, and then provides the rationale for and a clear exposition of each of the major science themes.

7. The proposals for science themes and the research directions included within them proposed by this contribution be considered by the Australian Antarctic Science Council during the development of a revised ***AASSP***, and that specific consideration be given to the development of interdisciplinary opportunities.

8. As part of the development of a revised ***AASSP***, the Australian Antarctic Science Council reflects the need for expansion of the science workforce within the Australian Antarctic Division to help deliver the full benefits of the science to be conducted under a revised ***ASSP***.

9. A revised ***AASSP*** should reflect the need for development of key elements of logistic capability, currently absent, but essential for further developing Australia's leading international science position and for understanding the AAT.

10. A revised ***AASSP*** includes specific guidance on the ways to ensure continuity of significant research support into the future, taking into consideration the requirements of delivering science that will ensure Australia's lead as articulated by the *Australian Antarctic Strategy and 20 Year Action Plan*.

Introduction

The Australian Academy of Science welcomes the opportunity to respond to the Australian Antarctic Science Council's call for advice concerning the *Revision of the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21* (hereafter the ***AASSP***).

The Australian Academy of Science promotes scientific excellence, disseminates scientific knowledge, and provides independent scientific advice for the benefit of Australia and the world. The Academy is made up of more than 500 of Australia's leading scientists, each elected for their outstanding contribution to science. The Academy has a long and substantive history of involvement in the development of Australia's Antarctic science programs, dating back to the Academy's foundation in 1954. Recently, the Academy provided extensive submission to the *20 Year Australian Antarctic Strategic Plan* (the Press inquiry)[i], provided oral evidence to the Senate Joint Standing Committee on the National and Capital and External Territories inquiry into *Australia's Antarctic Territory*[ii], and contributed advice to the *Australian Antarctic Science Program Governance Review*[iii].

In response to this request concerning the ***AASSP***, the Academy has consulted widely among its members and its National Committees which provide advice in specific areas of science. Included among the National Committees consulted is the National Committee for Antarctic Research, the Chair of which is an *ex-officio* appointment to the Australian Antarctic Science Council (AASC).

Australia has significant, wide-reaching, national strategic and scientific interests in Antarctica. These include maintaining a geopolitical claim to the continent, ensuring sustainability in Southern Ocean fishing industry, understanding Antarctic and Southern Ocean dynamics and their role in Australian climate variability, determining the potential magnitude and rate of Antarctic ice loss and the implications for managing future sea level rise, ensuring evidence-based environmental stewardship for the region (including the sub-Antarctic Heard and McDonald Islands, and Macquarie Island), and influencing the international direction of Antarctic governance and activity. Given the arrangements of the Antarctic Treaty System, national and strategic interests are inextricably linked.

As an original signatory to the Antarctic Treaty, Australia is assured its decision-making, or consultative status, in the Antarctic Treaty. However, its ability to influence affairs in the region is dependent on its scientific credibility. Those countries that are not original signatories to the Treaty only achieve decision-making status by conducting substantial research activity in the region. In consequence, sustained science leadership is the key to strategic influence. This leadership rests on science which is globally leading, has demonstrable national and international benefit, and/or the outcomes of which can be used to guide and support Australia's Antarctic Treaty System responsibilities and those to other international agreements. Developing sustained science leadership is possible only in the context of a strategic plan which takes a decadal view – a position adopted generally by the Academy in the development of its plans for other sectors of Australian research endeavour.

Background

Since the ***Australian Antarctic Science Strategic Plan 2011-12 to 2020-21*** was published, much has changed in the Australian Antarctic Strategic context and in global scientific understanding.

In a national context, both the *Australian Antarctic Strategy and 20 Year Action Plan*[iv] and the government response to the *Australian Antarctic Science Program Governance Review* have been published. The *Australian Antarctic Strategy and 20 Year Action Plan* does not provide an explicit science strategy, though it emphasizes the importance of science leadership for Australia's strategic interests in the Antarctic region. It also outlines a range of strategic infrastructure investments many of which are now underway, led by the Australian Antarctic Division (AAD) including the delivery of a new research vessel the *RSV Nuyina*, a new year-round air access facility (2.7 km runway proposed for the Vestfold Hills), a new research station to replace the old structure at Macquarie Island, and refurbishments to all of Australia's Antarctic research stations (Mawson, Casey, Davis). In addition, the plan highlights three pressing needs for Australia's Antarctic research effort: to better understand the role of Antarctica in the global climate system, to understand and conserve Antarctica's unique life forms, and to protect the Antarctic environment and support sound environmental stewardship in the region. The broader Australian Antarctic science capability also includes internationally leading research in other fields of considerable strategic benefit, such as Astronomy and interdisciplinary assessments of the region's future and its implications for the Earth System, including human society[v]. Several of these fields lie outside the National Science and Research Priorities[vi], but make significant contributions to Australian Antarctic science capability. Such broader capability is important in the context of the revision to the ***AASSP***.

The *Australian Antarctic Science Program Governance Review* response by the Government included several changes to the way Australian Antarctic science is overseen and developed. Notable in a science support context is the two substantial contributions for funds to scientific research in the form of the Antarctic Science Collaboration Initiative (ASCI - $50 M over 10 years) and the Australian Research Council led Special Research Initiative in Excellence in Antarctic Science (SRIEAS) ($56 M over 7 years). The former is now contributing to the Australian Antarctic Program Partnership (AAPP), administered by the University of Tasmania, and working through government organisations including the CSIRO, BoM and AAD (replacing the Antarctic Climate and Ecosystems CRC). An outcome on what science will be supported under the SRIEAS will be available only in November 2019[vii]. These two funding developments significantly add to the *ca*. $1 M p.a. that has so far been available to University-based researchers through the Australian Antarctic Science Program grants led and managed by the AAD. Yet, these latter funds remain important for encouraging new scientific questions and approaches. The Academy therefore recommends:

1. Despite the availability of the ASCI and SRIEAS funding, the Australian Antarctic Science grants program be continued, with increases matching the rising costs of research consumables and personnel, and preferably enlarged to meet the Australian capability in Antarctic research reflected through interest in the Special Research Initiative in Excellence in Antarctic Science call made by the Australian Research Council.

In an international context, interdisciplinary research to fully comprehend the future of Antarctic and Southern Ocean systems that are of global significance (such as sea level rise and carbon sequestration by the Southern Ocean) and to ensure environmental stewardship and the sustainability of Antarctic living systems and resources is now at the forefront of recognized research challenges as set out in the SCAR Antarctic and Southern Ocean Science Horizon Scan[viii]. Although disciplinary research to resolve outstanding questions, and to address new ones that have arisen, remains of critical importance, the value of complementing that work with interdisciplinary insight is now widely recognized. One notable development has been the growing appreciation for the importance of the Social Sciences and Humanities in providing previously missing perspectives on the requirements for successful adaptation to change and the achievement of policy success, including mitigation to reduce further change. This development is reflected in particular by the merger of the International Council for Science and the International Social Science Council to form the International Science Council[ix], to which the Academy adheres, and of which the Scientific Committee on Antarctic Research (SCAR)[x] is a member. Additional international developments include the outcomes of the Intergovernmental Panel on Climate Change's (IPCC) Special Reports on *Global Warming of 1.5°C*[xi] and on *The Ocean and Cryosphere in a Changing Climate* (to be finalized in September 2019)[xii]. Other research priority setting exercises including those conducted by the World Climate Research Programme[xiii] should also be considered.

These developments all have a significant bearing not only on the science questions that potentially now can be pursued thanks to new resources and infrastructure, but also those that are practicable over the next five years given the constraints brought by the infrastructure development timing, and those that actually go ahead in the SRIEAS owing to decisions yet to be made by the Australian Research Council. Thus, they have substantial bearing on a revision to the *AASP*. The Academy therefore recommends:

2. In revision of the ***AASSP*** close attention be given to how global leadership in Antarctic science will be maintained by Australia with significantly reduced access to the continent, sub-Antarctic and Southern Ocean, especially over the next five years. One potential solution is collaborative arrangements with other nations that cover whole of program interests.

Moreover, in the previous process for developing the ***AASSP***, an extended period was provided for the broadest consultation of the Australian Antarctic science community and the Australian research community more generally, including several 'town hall' meetings. These proved of great utility for obtaining a united perspective on science of global significance, national importance, and in which Australia could both lead and excel. The need to ensure an integrated clear voice for the Antarctic community in the development of a science strategy is a central theme underlying the nine recommendations of the *Australian Antarctic Science Program Governance Review*, the majority of which were supported by the Government in its response. The current timeline for the provision of advice is, by comparison, much compressed. In consequence, the opportunity for integration is more limited. The Academy therefore recommends:

3. In further development of the ***AASSP***, and in particular the specifics of research to be undertaken within each thematic area (known as Streams in the previous *AASSP*), broader consultation over a longer time span, including 'town hall' meetings in key locations, be undertaken.

The Academy also recognises that the developments in the way Australian Antarctic science is now structured and supported, including through the AAPP, SRIEAS and AAD, and with advice from the AASC, lend themselves to leadership of Themes and Streams from across the community of Antarctic researchers. Taking this approach will also help supplement and grow leadership in the area, especially given reduced numbers of scientific research staff within the AAD. The Academy therefore recommends:

4. Theme and Stream leaders (or their equivalents under a revised ***AASSP***) be sought from across the Australian Antarctic science community through an open process coordinated by the AASC, which then advises the Department of the Environment and Energy or its delegate.

Moreover, a range of developments across the Australian research landscape should also be recognised for the opportunities they bring. These include the establishment of the Australian Space Agency and interdependencies and overlaps between the ***AASSP*** and other national science strategies currently in formulation or under consideration, such as the climate science strategy on which the National Climate Science Advisory Committee is advising the Government, and Australia's 'Strategy for Nature 2019-2030' currently being formulated under Department of the Environment and Energy leadership in collaboration with state, territory and local governments.

Interdependencies among different Government science initiatives might further influence the way that a revised ***AASSP*** is implemented. For example, investment in research infrastructure through the *National Research Infrastructure Investment Plan* and *National Collaborative Research Infrastructure Strategy* will be needed to support a number of vital activities within the *AASSP* including marine observations (Integrated Marine Observing System), research vessel ship time (Marine National Facility), and climate modelling (ACCESS model).

In view of these developments, the Academy recommends:

5. Broad developments across the Australian research landscape be considered as part of the development and implementation of a revised ***AASSP***.

Finally, in considering the importance of the revised ***AASSP*** and its significance over the next 5-10 years in guiding Australian Antarctic Science, the need for easy access to and ready appreciation of its content by a wide range of audiences is important. The specific details of research areas and an account of the reasoning behind them are critical for the science community, but perhaps less so for a more general audience. Thus, the Academy recommends:

6. The revised ***AASSP*** be reduced in length such that it focuses on the significance of Antarctic science globally and the role Australia can play, highlights key strengths and opportunities for Australia as well as constraints and how they are to be managed, and then provides the rationale for and a clear exposition of each of the major science themes.

Science Themes

The majority of the Themes identified in the original ***AASSP*** remain relevant to Australian Antarctic Science today, but with the need for modifications to take into account new scientific developments and changes in national strategy, capability and resourcing. This section sets out, briefly, a set of proposed themes, rationale for them, and a synopsis of what science they might include. The Academy recommends:

7. The proposals for science themes and the research directions included within them proposed by this contribution be considered by the Australian Antarctic Science Council during the development of a revised ***AASSP***, and that specific consideration be given to the development of interdisciplinary opportunities.

Climate Processes and Change

The overall goal of Theme 1 of the ***AASSP*** remains relevant today, as do the high-level goals and key research questions of its component Streams. However, some revision is needed to reflect the substantial scientific progress made in the past decade, and the emergence of new areas of concern. The new strategic plan also needs to reflect the evolution of national and international policy drivers. Moreover, consideration should be given to developing two related themes under this broader area such as ‘Cryosphere processes and climate interactions’ and ‘Southern Ocean processes and climate/ice sheet interactions.’

Key discoveries in the past decade have further highlighted the global influence of ocean-atmosphere-ice interactions in Antarctica and the Southern Ocean, including:

- the East Antarctic Ice Sheet is more vulnerable and makes a larger contribution to sea level rise than thought;
- the Southern Ocean dominates ocean uptake and storage of anthropogenic heat and carbon (and is subject to strong and unanticipated variations in time);
- an unexpectedly rapid shift from record high to record low sea ice extent in recent years;
- ice shelf (and hence ice sheet) stability is influenced by multiple factors, including warming of the ocean and atmosphere and the presence or absence of sea ice;
- high-resolution ocean modelling and the incorporation of meltwater input to the ocean into is essential for capturing realistic deep-water formation and the magnitude of ocean warming at the ocean-ice sheet interface.
- new insights into trace metal sources and sinks and their influence on biological production and carbon export;
- new understanding of the impact of multiple stressors (warming, acidification, change in ocean stratification and light) on primary producers and the ecosystems that depend on them.

Motivated by these new discoveries, a new ***AASSP*** needs to include studies of key cryosphere processes such as - Iceberg calving and ice shelf collapse, meltwater ponding and hydrofracture, interactions of subglacial sediment and water with glaciers, solid Earth/sea level and ice sheet feedbacks, and investigations of past ice sheet behaviour including new proxies. The global importance of these processes to future rates of sea level rise mean that progress also needs to be made in incorporating these processes, or parameterisations of them, into ice sheet models that are coupled to ocean, atmosphere and Earth processes.

Fundamental observations that are required to enable/test robust model projections include - continental shelf and sub-ice shelf cavity mapping, glacier and bedrock geometry, ice shelf basal melt, geothermal heat flux, oceanographic measurements of warm water and its pathways, present-day ice sheet mass balance from space, and glaciological, geological and geomorphological constraints on past ice extent and rates of change, especially during comparable warm periods and leading up to the present.

The revised ***AASSP*** also requires a focus on ocean – ice shelf interaction, with a particular focus on East Antarctica; the drivers and impacts of change in Antarctic sea ice; processes controlling ocean uptake and storage of anthropogenic heat and carbon dioxide and their changes with time; assessments of the likelihood and consequences of climate feedbacks in Antarctica and the Southern Ocean; the sensitivity of Southern Ocean circulation to changes in forcing, including the overturning circulation, the Antarctic Circumpolar Current, and ocean currents near the Antarctic margin; and the impact of changes in physics and biogeochemistry of the Southern Ocean on marine life, including the impact of multiple stressors.

The existing plan has a strong emphasis on observing and understanding change in the Southern Ocean, cryosphere and atmosphere. This implicitly requires detailed process understanding of how the ocean, atmosphere and cryosphere, and their interactions, respond to changes in forcing and their trajectories of future change under difference emission scenarios. But it would be useful to make this dependence explicit in the revised plan.

Antarctica and the Southern Ocean influence and are influenced by climate phenomena at lower latitudes, so it is important that the scope of the ***AASSP*** includes these interactions. Notable examples include the influence of tropical climate modes (e.g. El Niño – Southern Oscillation and Interdecadal Pacific Oscillation, and new evidence of atmospheric teleconnections via the tropical Indian Ocean) on atmospheric circulation in the Antarctic and Southern Ocean region, mass balance of the Antarctic Ice Sheet, sea ice, and ocean circulation, and the ocean sink of anthropogenic carbon dioxide (strong uptake in the south, large storage in the north). To assess and understand the role of Antarctica in the global climate system, the ***AASSP*** must include the entire Southern Ocean (from the Antarctic continent to the subtropical front).

Terrestrial and Nearshore Ecosystems

The overall goals of Theme 2 remain relevant today, as do the high-level goals. Revision is required however to recognise several difficulties. First, the delineation of 'nearshore' versus 'Southern Ocean' ecosystems is entirely artificial and has in many respects hindered research. The Southern Ocean ecosystem does not operate this way, no matter how convenient it might be for other reasons to make such a distinction. Second, this distinction is not typically recognised in marine science generally. Third, even from a policy framework, the approach makes little sense because of the increasing collaboration on questions such as Marine Protected Areas between the Commission for the Conservation of Antarctic Marine Living Resources and the Antarctic Treaty's Committee for Environmental Protection. The distinction should not be maintained, and 'nearshore' system work should be transferred to a Theme focussing on Southern Ocean Ecosystems. If this distinction must be maintained, it should be well-justified in future plans and steps taken to prevent it from hindering excellence in Australian

Antarctic marine research. Where obvious synergies exist between work in terrestrial and marine systems, such as in remediation of pollution, specific cross-environment opportunities should be created for such work, rather than attempts to fit the entire Theme to single requirements.

Key discoveries in the past decade have emphasized the need to further develop understanding of terrestrial environmental change and the strategies required to mitigate and adapt to it:

- The expansion of ice-free areas as climates change will influence significantly habitable area and the distribution of terrestrial diversity so affecting the success of spatial protection;

- Drying thought to be associated with increasing windspeeds, in part a function of an increasingly positive Southern Annual Mode, is altering the composition of moss vegetation and changing the values of protected areas;

- Antarctic microbial systems are much more spatially distinct and functionally distinguishable than previously recognized, with remarkable characteristics enabling new insights into the field.

- Microbial systems in East Antarctica undertake unusual ways of supporting their lifestyle, including trace gas scavenging. Microbial systems here are providing a treasure trove for the discovery of microbes and microbial systems with previously unknown properties.

- Despite relatively stringent biosecurity measures, non-indigenous species continue to be recorded in the cargo or transport pathways to Antarctica, with some species establishing on stations, including those of Australia;

- New pollutants, including of a variety of forms, such as persistent organic pollutants and plastics continue to enter the Antarctic environment, and legacy pollutants may be released from melting ice.

These new discoveries, make it clear that a revised ***AASSP*** needs to include studies of key terrestrial processes such as – those determining spatial variation in microbial community structure and function, trends in the community composition and population dynamics of terrestrial systems to distinguish natural from anthropogenic signals, scaling of small-scale responses to changing water availability to whole landscape modelling across the Australian Antarctic Territory (AAT), projection of the efficacy of protected area mechanisms of conservation over the next 50 years, and alternative tools for biodiversity conservation, such as species protection.

Long-term data on sub-Antarctic and Antarctic sites can be combined with remote sensing technologies and repeated surveys to understand the trajectory of change of these systems and the value of conservation interventions. Few sites offer as effective a window into the interactive effects of local and global change as do those of the sub-Antarctic and Antarctic areas close to stations, and with the benefit that commitments to understanding Australia's World Heritage sites are included.

Australia remains a leader in the remediation of polluted sites and in understanding their impacts. As the impacts of new and legacy pollutants are appreciated across the broader Antarctic, Australia should continue to demonstrate leading environmental stewardship by maintaining and extending its leadership in the fundamentals of environmental pollution pathways and the most effective methods for remediating sites over small and large scales.

Much opportunity exists for closer interdisciplinary interaction with Themes 1 and 3 to provide whole of system forecasting for changes to the AAT and its implications for policy and governance, and for improving understanding of the benefits of Antarctic research to the Australian public. In particular, despite discussion of threshold sensitivities, or tipping points, across all three themes (e.g. sea ice change and the benthos, ice sheet change owing to the marine based nature of ice sheets or the role of ice rises, changes to water availability owing to pulse events and impacts on diversity) virtually nothing is known about them, how they might be detected, and what their impacts might be.

Southern Ocean Ecosystems

The overarching goal of theme 3 'Southern Ocean Ecosystems: Environmental Change and Conservation' in the AAS Strategic Plan remains relevant, however, the current focus should be broadened to allow new research directions focussed on Southern Ocean ecosystems defined both by strategic relevance and available capacity within the Australian research community. Research into Southern Ocean ecosystems and species should also play a role in interdisciplinary research, linking with physical science in several areas.

Evaluating the probability of different food web structures and ecosystem impacts arising under predicted physical (e.g. ocean currents, upwelling, sea ice) and chemical (e.g. ocean acidification, salinity) changes in the ocean and sea ice systems remains an important element. In addition, the integration of fisheries data into ecosystem models is necessary to assist in management decisions. Research in these areas will help determine how change will affect the productivity and sustainability of species and ecosystems and which key pelagic species are most vulnerable. These issues continue to be central in addressing priority science needs for government policy and resource management agencies.

Krill is an important keystone species and research on this species should be maintained. However, research that enables greater understanding of the broader state of the ecosystem, (including plankton, squid and fish - including icefish and toothfish), is also important and should be supported. Long-term ecosystem monitoring programs have received little support in recent years but play an important role in being able to detect change.

It is currently not well understood how Southern Ocean biochemical and ecosystem processes feed back to the climate system. Improved understanding of the nature and extent of change in ocean carbon sinks remains important in order to adapt to the impacts of climate change and is an important interdisciplinary research area.

There is need for research to understand the distribution and physical drivers of benthic marine ecosystems. Benthic ecosystems remain very poorly sampled in East Antarctica. Baseline information on the composition, diversity, distribution and connectivity of marine ecosystems is essential for identifying areas of high conservation value, testing ecoregional classifications and evaluating the performance of spatial management measures to protect vulnerable marine ecosystems and marine biodiversity in East Antarctica. This work will help evaluate the comprehensiveness, adequacy and representativeness of Marine Protected Areas or other ecosystem management tools.

All mention of 'evolution' in the current plan is related to climate and ice, but not fauna. Investigating the evolutionary history of Southern Ocean fauna enables several key questions to be addressed including how life has evolved in response to geological and climatic change, and in particular, during times of warmer climates. Research into the evolutionary history of marine benthos can also be used in an interdisciplinary framework to inform research in physical science, as genomic signatures of historic connectivity that persist in genomes of benthic animals can provide new constraints on the past behaviour of ice sheets.

Astronomy, Space Science and Radio Science

The high plateau regions in Antarctica contain the best sites on the surface of the Earth for most astronomical observations. As a result of the lack of a jet-stream over the continent and the smooth topography, the atmosphere is far more stable than that at any alternative site. Also, the low temperatures result in atmospheric emission and transparency that is far superior to any alternative site for infrared and terahertz observations.

These factors make it possible to conduct astronomical science from Antarctica that would be essentially impossible elsewhere. The questions that we can answer include resolving theories of the earliest history of the universe, searching for planets around other stars, and understanding the formation of black holes from neutron star mergers.

Some fields of astronomy from Antarctica - notably those conducted from the US Amundsen-Scott South Pole Station - have reached a mature stage of development. For example, the study of neutrinos using the IceCube detector, where the main Australian link is with the University of Adelaide School of Physical Sciences.

In optical, infrared, and terahertz astronomy we are at a critical juncture where the prototype experiments of the last decade at Dome A, Dome C, Dome Fuji, and Ridge A, will lead to major facilities, at the $10-100 million level, over the next decade and beyond. New facilities will likely be built largely by China at Dome A, to a lesser extent by France at Dome C, and with a possible contribution from Japan at the temporarily closed Dome Fuji. Australian astronomers have collaborated with astronomers from China, France, the US and Japan in Antarctica, and we expect to be valued partners in the new facilities.

There is now greatly increasing interest in Australia in space-related projects, spanning upstream (e.g. satellite and payload development) to downstream (e.g. data analysis and service provision) activities. Space Situational Awareness (SSA), is the monitoring and understanding of the Earth's immediate space environment, e.g., near-Earth objects, tracking of satellites, and space weather. Both France and China are actively interested in developing Antarctic facilities for SSA, and the Australian National University's Institute for Space would be a natural partner. Already several Australian groups and agencies are developing small satellites and missions, while in the near future we will likely see constellations of satellites, national flagship space projects, and new opportunities for space-based services. Almost certainly we will see Australian programs involving satellites in low altitude polar orbits. Australia formally recognises space weather as a national risk and it is essential that we undertake research activities which improve our understanding of Earth's near space environment and improve our forecasting of potential impacts on technological systems.

Antarctica's Antarctic stations are ideally located for studies supported or integrated with space projects since their geomagnetic field lines map to regions of the magnetosphere where key solar-terrestrial interactions and instabilities occur. In space science, studies of the Earth's magnetosphere from Antarctica have a long history, and involve the University of Newcastle Space Physics Group. Australia is an international leader in aspects of space weather science and monitoring and operates, through the Bureau of Meteorology's Space Weather Service, the World Data Centre for Space Weather. There are opportunities to develop a world-leading space weather forecasting and prediction capability by integrating observing capability spanning Antarctic to equatorial latitudes and linking this to theoretical studies underway in Australian institutions and agencies. Moreover, there will be opportunities for Australia to be involved in national and international space projects utilising our geographical advantages and ground assets.

The next generation of long-range ultra-fuel-efficient airliners will allow airlines to fly along great circle routes passing above Antarctica and the Arctic, realising greater economies to remain competitive and environmentally sustainable. Such operations will require ground-based monitors of cosmic rays and energetic neutrons to constrain radiation models which apply to middle latitudes. In this context the Mawson cosmic ray telescope will be an important asset. Furthermore, the Antarctic ionosondes will also become more important because of the need to support HF communication services.

Australia has key interests requiring detailed knowledge of the ionosphere. These include the JORN defence surveillance radars, the MWA and other radio astronomy facilities, all HF radio operations (e.g. for air services), and GNSS precise positioning and navigation services, all of which are affected by ionospheric dynamics. Data from radio sounders, magnetometers and other instruments on Macquarie Island are essential to improve the operation of these services, since a great variety of irregularities form in the auroral zone, above or near Macquarie, and propagate equatorward to Australia. It is important that these priorities are considered during development of the new station, and as an ongoing component of AAD science activities.

The neutral (non-ionised) and ionised parts of Earth's atmosphere are dynamically coupled. For example, it is now well established that the precipitation of energetic particles from Earth's Van Allen radiation belts affects atmospheric chemistry (NOx, HOx concentrations) and hence polar stratospheric ozone and surface level temperature. Details of the exact coupling mechanisms and the impact on weather and climate require further investigation. This requires coordinated studies using ground and spacecraft instruments and modelling, and should be a science priority.

Geodesy, Geophysics and Mapping

Despite substantial international efforts to acquire fundamental datasets relating to Antarctica's terrestrial, marine and sub-marine environments, major gaps remain and none more so than in AAT. The Australian Antarctic Strategy and 20 Year Action Plan makes a commitment to an *enhanced program of mapping and charting* in the offshore and onshore environments of AAT, and this was also supported in the Government's response to the Governance Review of the Australian Antarctic Science Program ("the Clarke review"). Mapping here is taken broadly to mean initial measurement, and time evolution of, terrestrial (geology and geomorphology), marine (geomorphology and sedimentology), and subterranean and subglacial (geophysical) environments. Geodesy pertains to fundamental measurements of the changing shape and gravity field of the solid Earth, and geodetic measurements underpin and enable reference frames/points to which many mapping activities are related. To bring these disciplines together under a united theme would enable research based on an enhanced mapping program to address key geoscience questions, as well as contributing more coherently to interdisciplinary research within other themes.

Delivery of a geodetic and mapping program requires a prioritisation plan based on the coverage of existing datasets, areas of key scientific interest and an understanding of strategic opportunities. An enhanced mapping program will enable Australia to develop tangible evidence of our sovereignty within the AAT and adjacent marine jurisdiction.

The delivery of the RSV *Nuyina* provides new capabilities and opportunities for detailed mapping of the seabed. Multibeam bathymetry mapping (and coincident sub-bottom profiling) needs to be undertaken on dedicated marine voyages to maximise the scientific benefit of this data. In addition, well-planned transit data will build our coverage and knowledge of seafloor environments and processes over time. The RSV *Nuyina* has the potential to reach parts of the AAT that have been rarely, if ever, visited. New onshore mapping in areas away from Australia's three continental stations can be facilitated by the expanded capacity of the new vessel. Integrated mapping from onshore to offshore would provide a source to sink view of ice sheet, earth and climate history, and their implications for modern environments, ice sheet stability and earth processes. The current capabilities for geoscience research on the RSV *Nuyina* have great potential, but key equipment, such as for seismic acquisition, are not currently available. Resourcing to support this and/or equipment sharing agreements with the Marine National Facility is vital to support full scientific utilisation of the new vessel, noting that operation of this equipment also requires support from specialised crew and support staff. Scientific support staff are not fully funded within the RSV *Nuyina* budget, limiting the availability of the ship for scientific purposes.

Airborne geophysical surveys should be planned to overlap with new marine and terrestrial priorities to ensure a multidisciplinary approach. Australia does not presently have an airborne geophysical capability for Antarctic operations. The development of drone-based remote sensing activities, including long-range platforms, is an exciting emerging opportunity that would allow cost-effective increases in mapping and monitoring; a plan for the development and operation of such a facility is required. Commercially provided high-speed satellite-based data communications are under development that should allow rapid and open data provision, while reducing the logistics burden required to manually download sensors.

The scientific outcomes of mapping and charting can contribute across multiple themes, as well as address future research needs that could be incorporated under a new theme include:

Terrestrial geology and geomorphology

Terrestrial geology and geomorphology mapping can address a range of research and conservation needs, including understanding landscape vulnerability and resilience through knowledge of landscape properties and processes; geo-conservation by highlighting sites of geological significance; biological domain mapping by understanding the influence of landscape properties, bedrock influence on water availability and the distribution of minerals and energy for biota; ice sheet dynamics through studies of geothermal heat flux, sub-ice topography, crust and mantle properties; past ice sheets and sea level response by analysing landscape history of ice flow and erosion, geomorphic records of past ice sheet response and geological provenance mapping; and investigating the geological evolution of the Antarctic continent.

Marine geomorphology and sedimentology

Marine geomorphology and sedimentology provides datasets that can contribute across multiple themes, including: oceanographic modelling by mapping pathways and obstacles to flow; past ice sheet dynamics by interpreting geomorphic records of past ice sheet advance and retreat; past oceanographic and climate variability by providing the sedimentological context for selection of sediment core sites; biodiversity protection by identifying the diversity of seafloor habitats and key ecological features; and supports strategic operational requirements such as charting for safe navigation, infrastructure development and facilitating search, rescue and recovery operations.

Geodesy

Geodetic research is essential for quantifying the contribution of the ice sheet to sea level through data relating to changes in ice sheet elevation, mass and velocity; it provides information on three-dimensional motion and deformation to enable understanding of plate tectonics, volcanic deformation and viscoelastic processes due to surface loading changes and near- and far-field seismicity; and it enables sea-level studies from tide gauges and satellite altimeters.

Airborne and terrestrial geophysical surveys

Airborne and terrestrial geophysical surveys inform a range of research questions including: past ice sheet dynamics through understanding of bedrock topography, landscape and ice sheet evolution and structure; ice sheet sensitivity and vulnerability by allowing assessment of meltwater, subglacial lakes, bedrock topography, grounding lines, ice thickness and accumulation; continental evolution through geological reconstructions and understanding of the thermal structure of the Antarctic lithosphere; and solid Earth structure and rheological properties, allowing., tectonic reconstructions and modelling glacial isostatic adjustment.

Frontier Science

The ‘Frontier Science’ element of the current ***AASSP*** is exceptionally important for providing an avenue to explore new ideas and technologies. This area should be maintained since no other route exists for exploring new avenues of research in the current way in which the large funding allocations to Australian Antarctic Science have been made. The term 'Frontier Science' should be revised, however, since so much evidence exists that 'frontier science' has been a relatively common feature across all three themes over the past decade. Consideration should be given to renaming this area to something like 'Future Science and Technology'.

From Here to the Future

New funding and new infrastructure commitments are an exceptionally welcome development for Australian Antarctic science which help stem the problems of declining research capacity and output identified in a series of previous reviews.

Nonetheless, it should be recognised that science capacity within the Australian Antarctic Division remains much reduced and science budgets there under considerable pressure. Much value lies in having experienced, long-term scientific staff at the AAD. They are essential in terms of their science contributions, experience to help development of new science, interpretation of the policy relevance of research outcomes from across the Australian Antarctic science program, and for representing Australia's national interests alongside their colleagues from other institutions at major international meetings and forums. Currently, much of this is not possible or is being under-delivered owing to current circumstances. The Academy therefore recommends:

8. As part of the development of a revised ***AASSP***, the Australian Antarctic Science Council reflects the need for expansion of the science workforce within the Australian Antarctic Division to help deliver the full benefits of the science to be conducted under a revised ***ASSP***.

Logistics capability to support some areas of extant and developing capability in Australian Antarctic science also require consideration. These include, for example, aircraft for geophysics programs and technical capability in support of atmospheric, marine and terrestrial science. The Academy therefore recommends:

9. A revised ***AASSP*** should reflect the need for development of key elements of logistic capability, currently absent, but essential for further developing Australia's leading international science position and for understanding the AAT.

In addition, despite the extended funding time frames of 10 years (ASCI) and 7 years (SRIEAS), these are, in reality, short funding periods given the long-term nature of Antarctic research and the planning required to give effect to leading international science. Moreover, even within these welcome funding contributions, the total funding does not fully recover the requirements for utilising the extraordinary infrastructure capabilities that are coming on line for Australian Antarctic science (e.g. through the *RSV Nuyina*). Therefore, the Academy recommends:

10. A revised ***AASSP*** includes specific guidance on the ways to ensure continuity of significant research support into the future, taking into consideration the requirements of delivering science that will ensure Australia's lead as articulated by the *Australian Antarctic Strategy and 20 Year Action Plan*.

[i] Press, A.J. (2014) *20 Year Australian Antarctic Strategic Plan*. Available at: http://20yearplan.antarctica.gov.au/final-report

[ii] The final report of the Senate inquiry (2018) is available at: https://www.aph.gov.au/Parliamentary_Business/Committees/Joint/National_Capital_and_External_Territories/AntarcticTerritory/Report

[iii] The review report and the government response (2018) are available here: http://www.environment.gov.au/antarctic-review

[iv] Available from: http://www.antarctica.gov.au/about-us/antarctic-strategy-and-action-plan

[v] Rintoul, S.R. et al. (2018) *Nature* 558, 233. Available from: https://www.nature.com/articles/s41586-018-0173-4

[vi] Information available from: https://www.industry.gov.au/data-and-publications/science-and-research-priorities

[vii] Information available from: https://www.arc.gov.au/grants/linkage-program/special-research-initiatives/special-research-initiative-excellence-antarctic-science-srieas

[viii] Kennicutt, M.C. II et al. (2014) *Nature* 512, 23 Available from: https://www.nature.com/news/polar-research-six-priorities-for-antarctic-science-1.15658; Kennicutt, M.C. II et al. (2019) *One Earth*, doi: 10.106/j.oneear.2019.08.014. Available from (20 September 2019): https://www.cell.com/one-earth/home

[ix] Information available from: https://council.science/about-us

[x] Information available from: https://www.scar.org/

[xi] Information available from: https://www.ipcc.ch/sr15/

[xii] Information available from: https://www.ipcc.ch/report/srocc/

[xiii] Information available from: https://www.wcrp-climate.org/