Arctic Portfolio Review

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Summary of Recommendations

It is recommended that ARC be re-constituted as three standing *programs* that invite proposals using one or more defined *approaches*. The programs are:

1. Natural Sciences and Systems (NSS)
2. Social Sciences and Systems (SSS)
3. Coupled Human-Natural Systems (CHNS)

These three programs would enable funding opportunities for all types of research historically supported by ARC in a framework that more clearly defines their logical home. Within each of the three programs the committee recommends that investigators self-identify no more than two general approaches to ensure that attention is paid to the different kinds of investigation that might be supported. The approaches are:

1. Deep Dive Investigation
2. Strategic Envisioning
3. High Risk and Exploratory Research
4. Synthesis and Integration
5. Long Term Perspectives

Additional recommendations are:

1. Program managers should be encouraged to seek opportunities to include new scientific directions and under-represented disciplines, with guidance from strategic envisioning processes led by the research community.
2. More attention should be paid to maintaining consistent institutional memory within ARC. This will ensure that guidance, particularly for early career researchers, will be consistent over time and between staff.
3. Program managers should be encouraged to pay particular attention to proposals that include the development of theory, instrument, algorithm or other technology. Guidance to proposers that these foci are valued should be unambiguous.
4. The feasibility of Arctic Graduate Research Fellowships should be explored.
5. The role of community engagement in scientific research is sufficiently complex that NSF program managers, with knowledgeable researchers and Arctic community members, should consider ways to support and assist Arctic investigators seeking to implement engagement.
6. Funding success rates should be routinely made public, and broken down by program within each Directorate, and this information included in new solicitations.

1. Introduction

The Arctic Portfolio review was requested by the Office of Polar Programs Advisory Committee (AC/OPP) and Arctic Sciences Section (ARC) Director Simon Stephenson to assess whether the balance of investments in science programs, and the supporting logistics capabilities and facilities, are aligned with current and near-term needs of the Arctic research community. The review is forward-looking, focusing on the period 2019 to 2023. The Arctic Portfolio Review Committee was asked specifically to

1. recommend the critical programmatic capabilities needed to enable progress towards building a vibrant and relevant scientific program; and
2. recommend the balance of investments in the new portfolio of grant programs, facilities, and other activities within budgetary constraints.

The committee was instructed to consider changes in programmatic structure, including reduction and elimination of programs, divestment of facilities, augmentation of current capabilities, and workforce development.

The 16-member committee was constituted in March 2018 and represents a balance of observational, experimental, analysis, and modeling practitioners and of social (3) and natural (13) scientists. Committee members included 8 women, 2 early-career scientists, and 1 member who has never received OPP funding. The committee met in person on one occasion and conducted 6 teleconferences over the course of twelve months to finalize this report.

In addition to deliberations by the committee, the process was informed by a community survey to ensure that no critical issues were missed. The survey, circulated widely among ARC investigators, yielded 215 responses and revealed three primary sets of perspectives (factors). Factor 1 emphasized the importance of social science and interdisciplinary research. Factor 2 underscored the pivotal role of NSF in supporting pan-Arctic natural science. Factor 3 articulated a pragmatic concern for supporting logistics. Results of the survey did not dictate the conclusions of this report, but provided information on the breadth of perspectives among Arctic researchers. Key issues addressed by the survey included the geographic scope of research, coordinated research strategies and field programs, and the importance of field work logistics support.

2. Review of Present Structure

The committee aimed to develop an ARC structure that is more effective in supporting transformative research. While the data shows that Arctic researchers are highly productive with regard to peer-reviewed publications, training and mentoring, awards and reputation, some improvements would enhance the progress and impact of the Arctic Sciences Section. The key recommendation of the committee is to simplify the ARC structure, with the purpose of rebalancing the effort among the resulting portfolio of activities and providing more specific guidance to the research community. This

recommendation is based on a number of observations regarding the present structure and balance of investments, responses from the survey, and a range of relevant reports from NSF as well as from the International Arctic Science Committee, the US National Academy of Sciences, and the University of the Arctic.

The first and most critical element reviewed by the committee was the distribution of disciplines funded. The committee observed that some programs within ARC have become very focused. These programs were seen by some committee members and some survey respondents as overly restrictive in the disciplines that were supported. For example, several researchers observed that the Arctic System Sciences (ARCSS) program had reduced emphasis on social science research over the last decade or so (Figure 1), and presently maintains a focus instead on modeling and analysis of system feedbacks. The active portfolio of ARCSS projects at present comprises 117 awards representing $61M in funding to date. Projects driven primarily by social science questions are represented in $2.7M in expenditure across 7 projects, of which one project on oil-field infrastructure development accounts for more than half of that expenditure. Indeed, some respondents to the community survey felt that truly interdisciplinary research focusing on the coupling of human and natural systems had an uncomfortable fit in the ARCSS program, compared to, for example, the NSF SBE/GEO CNH (Coupled Natural-Human Systems) program or the NSF Belmont Forum, the ArcSEES program, and the NNA (Navigating the New Arctic) Big Idea. As a result, the committee concluded that emphasizing a coupled human and natural systems approach in a separate program would better

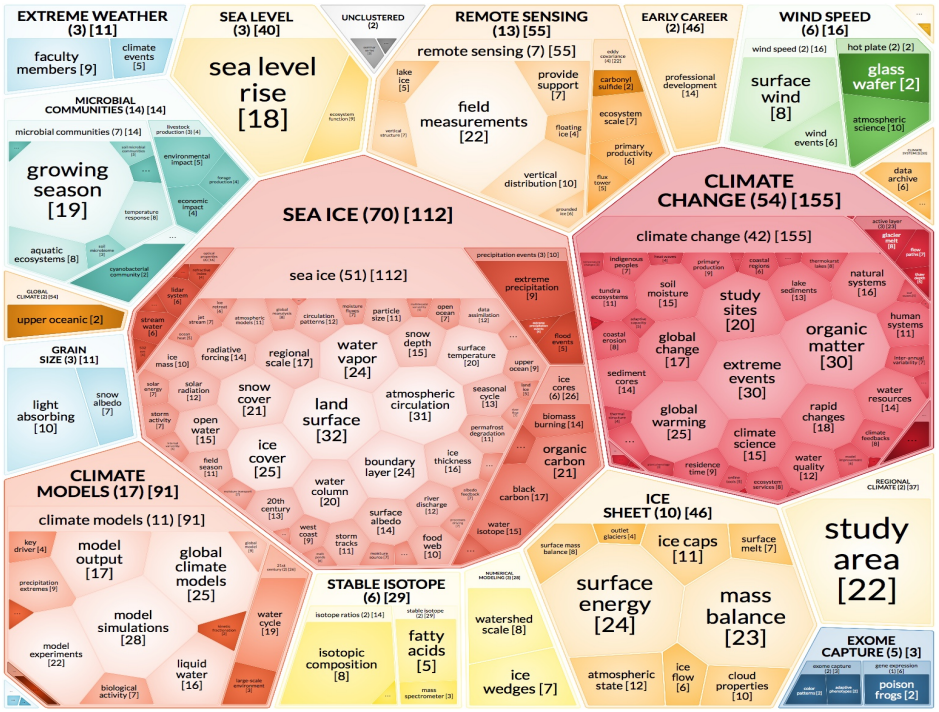

Figure 1. Text analysis of ARCSS-funded projects (key words, titles and summaries) for the period 2003-2017. Number of projects with key words belonging to the topic in parentheses. Number of documents in which the key word appears in square brackets.

encourage transformative research in this area (see Section 3.1). Other respondents to the survey noted that the Arctic Social Science Program (ASSP) is missing key disciplines such as economics (Figure 2), and the Arctic Observing Network (AON, not shown) is missing key disciplines such as archaeology. That said, it is apparent that proposal pressure in ASSP is lower on average than the other programs: ASSP comprised 17% of the proposals received over the period 2003-2017 and funded on average around 60% of these (Figure 3). In contrast, the Arctic Natural Systems program (ANS) received 56% of proposals over the same period, but yielded a 23% average success rate. (This went up to 47% in 2018 as the removal of deadlines reduced proposal pressure.) Arctic Observing Network success rates have been much more variable, depending on resource availability and program structure. To place this in context, the *Arctic Research Publication Trends Pilot Study* found that worldwide over the period 2011-2015, 12% of Arctic peer-reviewed journal articles in fields funded by ARC were identified as purely social science (by Scopus Subject Area: earth and planetary sciences, agricultural and biological sciences, environmental science and social sciences). Peer-reviewed books and book chapters, prevalent ways of publishing in many of the social sciences, were not assessed.

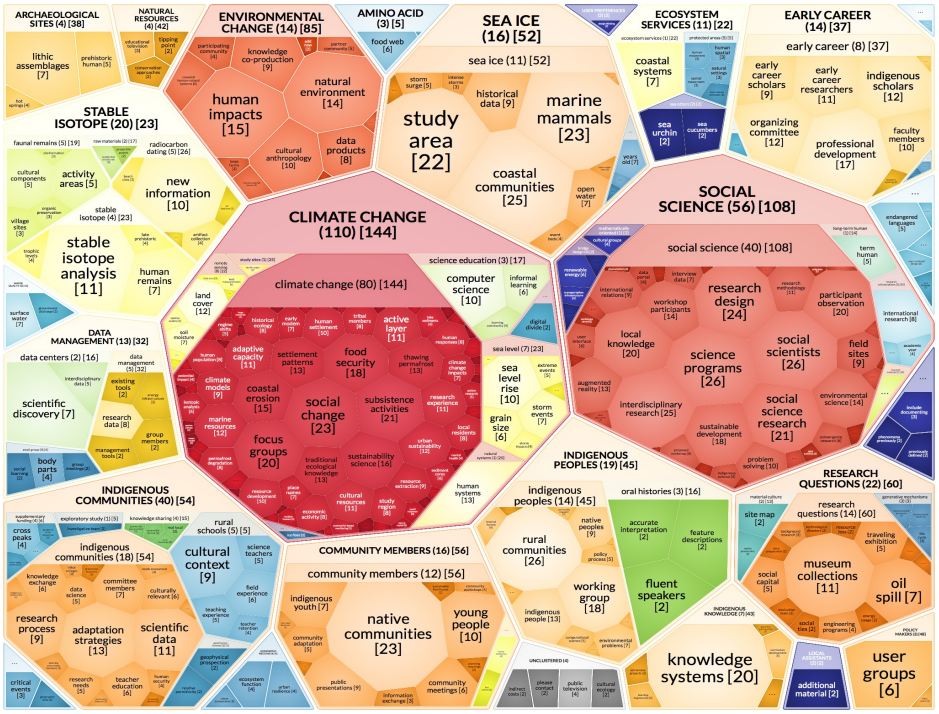

Figure 2. Text analysis of ASSP-funded projects (key words, titles and summaries) for the period 2003-2017. Number of projects with key words belonging to the topic in parentheses. Number of documents in which the key word appears in square brackets.

The disparities in proposal pressure and success rate, the uncomfortable fit of social sciences in the ARCSS program, and the potential for missed opportunities, together raise a critical question with regard to disciplinary balance among natural sciences projects, social sciences projects, and interdisciplinary projects. The proposal pressure in the context of global publishing averages suggests

that ARC as a whole is a reasonably balanced program, but the distribution of disciplines within ASSP suggests that there are Arctic social scientists who are not writing proposals to ARC. The question arises then, is this a matter for concern? There exist a range of perspectives on this.

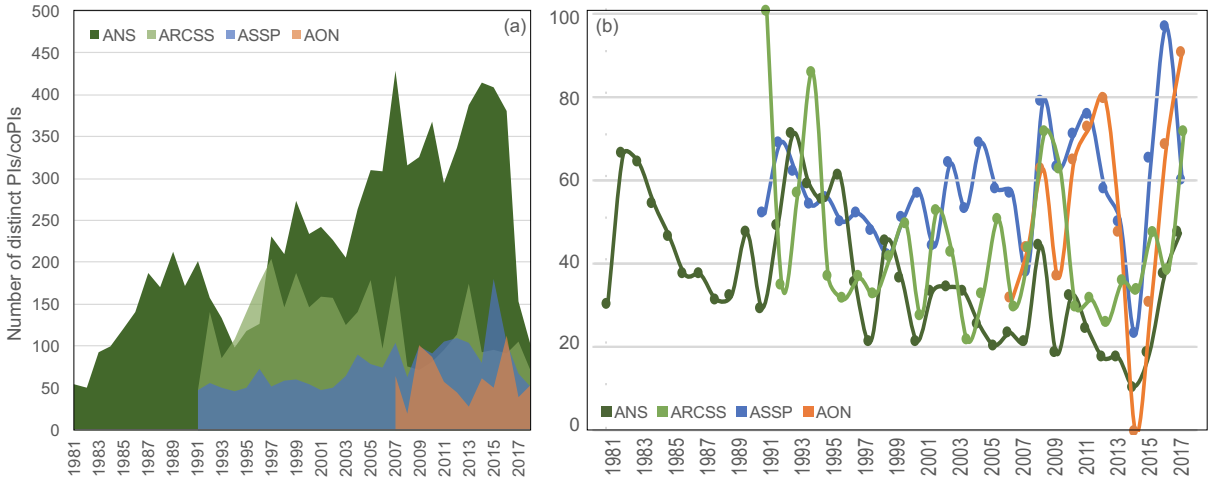

Figure 3. An analysis by ARC program from 1981 to 2018, showing (a) total number of distinct investigators and (b) the fraction of proposals awarded of those submitted, or success rate. Note that (i) all success rates went up in 2009 due to the federal stimulus package; (ii) ANS, ARCSS and AON success rates went up in 2018 since deadlines were removed, and (iii) the success rate of 100% for ARCSS in 1991 is spurious as this was a program initiation call.

For example, some survey respondents observed that they do not always know where to find a "home" for their research ideas. This perception ranged from proposers seeking to implement international collaborations, to researchers in under-represented disciplines, to early career proposers in general. While many researchers understood that they could have a conversation with a program manager when they were uncertain, other researchers did not. Further, it was not clear whether the guidance received was consistent over time or across program managers.

The broader context may be relevant also. Worldwide, the fraction of peer-reviewed journal articles in the social sciences, compared to the natural sciences, remains small. Conversely, the proportion of peer-reviewed books and book chapters in the social sciences is higher than the natural sciences, but their impact can be difficult to quantify. With regard to Arctic research specifically (Figure 4a), the trends suggest that the proportion is growing in social sciences, while remaining relatively flat in other fields funded by ARC. The field-weighted citation impact of Arctic social sciences, which measures the number of citations per publication compared to the field average as a proportion of the global average, is growing rapidly (Figure 4b). Further, Arctic natural sciences are cited at a higher rate than natural sciences globally, suggesting that Arctic natural science research has a greater than average impact and that Arctic social sciences are increasing in their impact. As noted, it is a challenge to determine these statistics for peer-reviewed books in any field and for inter-disciplinary research.

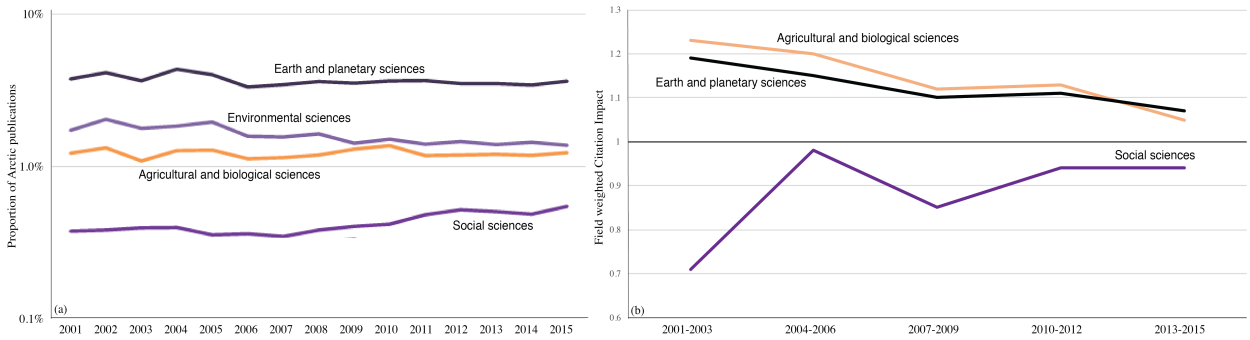

Figure 4(a) Proportion the world total of peer-reviewed articles that relates to the Arctic (log scale) and (b) field-weighted citation impact for FOS categories of Arctic research, 2001-2015 by Scopus Subject Area, 2001-2015 (Arctic Research Publication Trends). Discipline categories and colors determined by Arctic Research Publication Trends but for the purposes of ARC comparisons we consider Earth and planetary sciences and Agricultural and biological sciences to cover fields grouped as natural sciences in ARC. Environmental sciences may by cross-, multi- or inter-disciplinary but are included for completeness. Engineering and medical sciences are excluded from this analysis. Environmental sciences data are not available for citation impact.

Uncertainties regarding the impact of books aside, these data suggest that Arctic natural sciences continue to "punch above their weight" relative to the rest of the globe, while Arctic social sciences are growing, but their impact remains slightly below the global average for all social sciences. This may indirectly support the survey finding that key disciplines are missing from the ASSP portfolio. It is indeed probable that a higher profile in the Arctic for disciplines such as economics and policy would improve the impact of journal publications in Arctic social sciences (see, for example, Table 1).

Second, the committee observed that the development and implementation of transformative research benefit from a combination of opportunities for strategic planning within the scientific community followed by clear messaging in resulting announcements of opportunity. Structures to encourage this mode of researcher-driven strategic planning have been less evident in recent years. Furthermore, there are conflicting messages from NSF program managers as to how to obtain support for "ground-up" community planning activities, and the mechanism of obtaining small grants for such community

Journal Category (ISI)	**Number of Journals**	**Aggregate Impact Factor**
Evolutionary Biology	49	3.916
Ecology	160	3.281
Meteorology and Atmospheric Sciences	86	3.143
Oceanography	64	2.041
Public Administration (Policy)	47	1.905
Economics	353	1.766
Anthropology	85	1.656
Political Science	169	1.535
Sociology	147	1.466
Cultural Studies	40	0.731

Table 1. Journal Citation Reports from ISI for a selection of disciplines represented in ARC, drawn from approximately 12,000 scholarly and technical journals and conference proceedings from more than 3,300 publishers in over 60 countries/territories.

activities is cumbersome and slow. This threatens the potential of these efforts. Examples of past "ground-up" development resulting in announcements of opportunity include the Surface Heat Budget of the Arctic, Arctic Freshwater Integration Study, Shelf-Basin Interactions project, Arctic Transitions in the Land-Atmosphere System program, and the Bering Ecosystem Study. A recent – broader – strategic envisioning effort is embodied by the series of Arctic Horizons workshops, although this has not resulted in an announcement of opportunity at the time of writing. A common thread was observed in the planning efforts that result in significant scientific advances: the active support and participation of an engaged NSF program manager.

Third, key methodological investments are required to advance Arctic research. For example, some survey respondents observed that support for fundamental theoretical advances is not as prominent as it should be. Furthermore, the committee felt that there should be more investment in research tools – observations, instruments and models[1]. Advances in cyberinfrastructure that explicitly support Arctic research are limited across the NSF.

Fourth, there is a growing disquiet among investigators regarding the impact of proposal success rates on their decision processes for taking on graduate students. Because funding is less reliable, graduate students often are not admitted to a degree program until after a project is funded. Earning a Ph.D. generally takes considerably longer than the average funded project duration of three years, and graduate students typically spend their first two years focused on coursework. The delay in admission until support is secured combined with the initial focus of coursework has the unintended consequence of graduate student focus being out of phase with funded project activities. The research experience of graduate students is diminished, and faculty can struggle to maintain continuous support for students. The committee felt that this problem has a direct impact on the goal of increasing diversity and inclusion in Arctic sciences.

Finally, there are ongoing concerns that collaboration techniques and research protocols with Arctic communities need further elaboration and wider understanding among Arctic researchers. Community engagement is a norm for some researchers but less common for others. Some researchers have experienced problems, including stakeholder fatigue or unfamiliarity with IRB (Institutional Review Board) procedures.

[1] The committee notes that the NSF Engineering program presently funds approximately $1.7M in a small number of instrument development grants that have an Arctic focus, and these kinds of cross-directorate partnerships are to be encouraged.

3. Recommendations

The key recommendation of the committee is to simplify and clarify the ARC structure as proposed in Section 3.1 below. In addition to this major recommendation, the committee also suggests a series of minor or specific recommendations in Section 3.2.

3.1. Proposed Structure

It is recommended that ARC be re-constituted as three standing *programs* that invite proposals using one or more defined *approaches*. The programs are:

1. Natural Sciences and Systems (NSS)
2. Social Sciences and Systems (SSS)
3. Coupled Human-Natural Systems (CHNS)

These three programs would enable funding opportunities for all types of research historically supported by ARC in a framework that more clearly defines their logical home, while also being explicit in encouraging the development of more human-natural systems research (Figure 5). Activities that include observational components on a range of time scales, instrument development and laboratory research, model development and analysis, co-production of knowledge with Indigenous Arctic communities, and theoretical investigations are acceptable in any of these three programs. Two additional areas of investment in ARC – cyberinfrastructure and education – are recommended for increased investment through supplements to existing projects or explicit calls for proposals, but not as separate programs. This may include graduate student fellowships specifically for Arctic research and may include co-funding with other non-Arctic programs such as the Office of Advanced Cyberinfrastructure.

It is recognized by the committee that this recommendation has a substantive impact on the job descriptions of existing ARC staff, including particularly the program managers of existing programs. As such, we encourage OPP management to consider creative and supportive means to transition current staff to the new structure. This would ensure that the structural changes are underpinned by appropriate support for program manager vision.

While this simplified structure is intended to enable transformative research, it is recognized that there needs to be greater clarity in messaging the types of projects that can be considered. The committee recommends that ARC use project approaches to provide consistent and clear guidance. The approaches are:

1. Deep Dive Investigation
2. Strategic Envisioning
3. High Risk and Exploratory Research
4. Synthesis and Integration
5. Long Term Perspectives

The balance of investments across programs and approaches depends in part on proposal pressure, but a recommended starting point for assessing the balance of investments is noted here. Committee considerations assumed that the total amount of funding available increases at least with inflation over the 2019-2023 timeframe, such that logistics support is maintained or slightly increased relative to 2017 dollars (see Section 6.1). Natural sciences support should be maintained through direct support under NSS, as well as from contributions to CHNS and Cyberinfrastructure, and with the bulk of logistics costs. CHNS is envisioned as being small initially, but growing over time depending on proposal pressure and scientific advances, and with the development of the broader portfolio of Navigating the New Arctic. SSS support should be increased relative to ASSP to allow for a broader range of disciplinary coverage.

This proposed structure is a significant and forward-looking advance for the conduct of NSF-funded Arctic research, an advance that embodies both the excellence of our foundations and the challenges ahead. It embraces the thinking underpinning the Big Idea approach. It seeks to clarify and secure processes that support excellent science of all kinds. The committee recognizes that this presents a substantial re-orientation for the research community and supports any efforts to move in this direction, while also noting that the structure is likely to function as intended if implemented as a package.

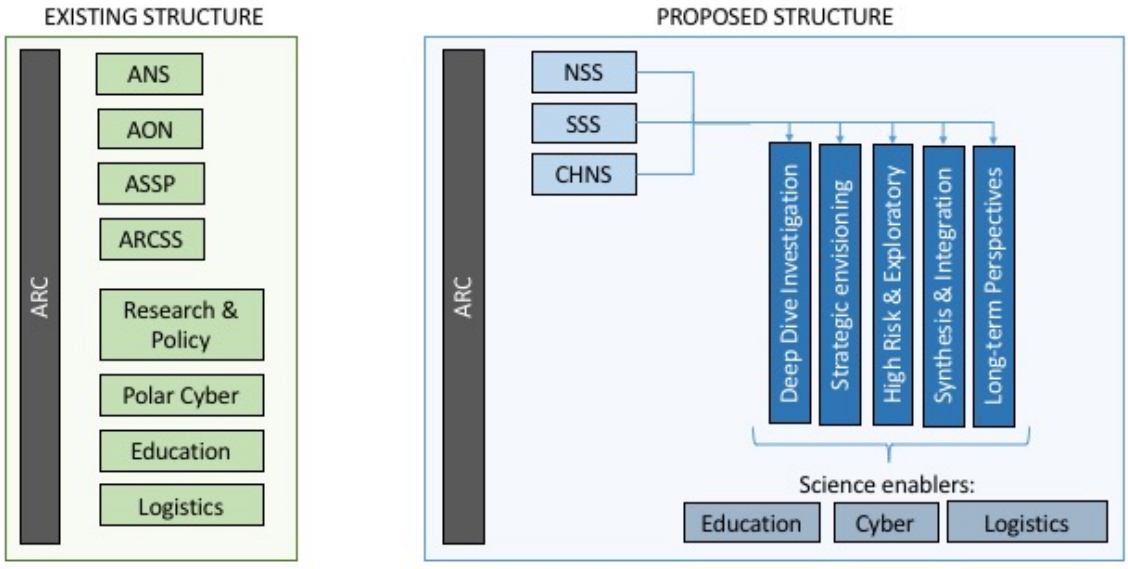

Figure 5. Proposed new structure for ARC

3.2. Other Recommendations

1. Program managers should be encouraged to seek opportunities to include new scientific directions and under-represented disciplines, with guidance from strategic envisioning processes led by the research community (see Section 5.2.)

2. More attention should be paid to maintaining consistent institutional memory within ARC. This will ensure that guidance, particularly for early career researchers, will be consistent over time and between staff.
3. Program managers should be encouraged to pay particular attention to proposals that include the development of theory, instrument, algorithm or other technology. Guidance to proposers that these foci are valued should be unambiguous.
4. The feasibility of Arctic Graduate Research Fellowships should be explored.
5. The role of community engagement in scientific research is sufficiently complex that NSF program managers, with knowledgeable researchers and Arctic community members, should consider ways to support and assist Arctic investigators seeking to implement engagement.
6. Funding success rates should be routinely made public, and broken down by program within each Directorate, and this information included in new solicitations.

4. Program Descriptions

4.1. Natural Sciences and Systems

The Natural Science and Systems (NSS) program is open to proposals that address physical, chemical and biological aspects of the Arctic system. Proposals may focus on specific system components such as ecosystem productivity, permafrost dynamics, atmospheric dynamics, or sea ice variability or proposals may more broadly address syntheses, interconnections and feedbacks among different components. For example, understanding changes in Arctic Ocean primary productivity from a systems perspective would naturally address how changes in sea ice extent and thickness that alter light penetration into the Arctic Ocean relate to changing sea ice dynamics and thermodynamics, which then necessitates addressing linkages with both atmospheric and oceanic forcing. NSS proposals may use modeling, observational, theoretical or laboratory approaches or any combination. This may include field work, analysis of existing data, paleoclimate studies, or the use of or development of physically-based numerical, statistical and conceptual models. NSS proposals may make strong use of satellite data, aircraft remote sensing data, and GIS approaches. Sustained observations are important to understanding the changing Arctic system. Observational programs may also include traditional ecological knowledge or partner with local community observers. Included are the types of proposals that would formerly have been submitted to ANS, AON and ARCSS.

4.2. Social Sciences and Systems

The design of a new Social Sciences and Systems (SSS) program is the beneficiary of substantial existing strategic planning through the Arctic Horizons process, which resulted in recommendations for growing support for social science research in the following areas: the intersections of culture and the environment, the forces on and impacts of economic and demographic changes, the study of social and political institutions, and the understanding of local and regional identities. For example, research

on long-term trends in socio-cultural or economic systems, public policy responses to ecological changes, Indigenous-led research on non-Western ontologies, or the impact of global markets on Arctic industrial development would all be encouraged under SSS. Social science grounded in co-production of knowledge with Arctic communities is encouraged where appropriate. Proposals may incorporate empirical, theoretical, and longitudinal research in sociology, archaeology, anthropology, economics, geography, history, linguistics, law, policy and political science. The program is open to studies of the past and scenarios for the future, at any scale from the local to the pan-Arctic, and including research that investigates where Arctic social dynamics and systems influence global social systems. Included are the types of proposals that would formerly have been submitted to ASSP, AON and ARCSS.

4.3. Coupled Human-Natural Systems

The Coupled Human-Natural Systems (CHNS) program funds proposals that advance understanding of processes that involve interactions between the natural world and cultural, social, legal or economic systems. These interdisciplinary projects should seek to identify key social or natural forcings, feedbacks and non-linear responses in a local, pan-Arctic or Arctic-global perspective. Researchers representing disciplines from both the natural and social sciences fields must be involved. Projects may include empirical work in the field or using archival data, the feasibility, use or development of predictive tools, exploration of emergent characteristics of the coupled human-natural system, or other approaches as appropriate. Examples might include environmental risk distribution across socio-economic systems, migration as a response to sea level rise, or Indigenous cultural responses to evolving ecosystems. Proposals must clearly identify how the results of the research will enhance understanding of the ways in which natural and human systems interact. Projects associated with the Navigating the New Arctic Big Idea are likely to link well with or fall within this program. Included are the types of proposals that would formerly have been submitted to AON and ARCSS.

5. Approaches

Within each of the three programs described above, the committee recommends that investigators self-identify one or two (*but no more*) general approaches. This would ensure that attention is paid by program managers and researchers alike to the different kinds of investigation that might be supported, from longitudinal observations to speculative new methodologies to workshops and networks.

5.1. Deep Dive Investigations

Distinction can be made between an integrated system-scale study and a tightly-focused, in-depth process study, the latter termed here a "deep-dive" study. Studies will be supported that address processes and phenomena that are especially important in the Arctic, although they may not be confined to the Arctic (e.g., what happens in the Arctic has influences beyond the Arctic or vice versa).

As a result, insights through in-depth analysis of a discipline-specific research question are likely to yield important theoretical advances that are significant in a wider context. Methods may include the collection and analysis of field data in a specific site, population or archive, or application of a numerical or statistical model. While a deep-dive study should recognize that the research question being asked is implicitly embedded within a coupled system or a more complex context, such connections do not have to be explicitly addressed. Studies of both natural and social systems are encouraged.

5.2. Strategic Envisioning

Workshop, research network, and working group grants have played an important role over the past two decades in bringing together investigators to explore strategic questions and to develop research directions. Envisioning activities should be aimed at developing disciplinary and interdisciplinary research communities to identify and explore strategic research questions that have the potential to lead to important new insights. Activities inclusive of a broad research community or that bring investigators new to the ARC program are especially encouraged. An example of a successful recent effort was the Arctic Horizons series of workshops that explored the future of Arctic social sciences. A similar series of workshops under ARC could help in developing a programmatic vision for the recommended CHNS and NSS programs. Focused strategic envisioning exercises, including single workshops and research networks, are also appropriate for funding, as are proposals for time-limited program office support of research coordination. Pathways towards these types of activities, including guidelines for timelines of submission and program response, potential funding levels, review procedures, and desired elements for the projects should be made clear and transparent.

5.3. High Risk and Exploratory Research

All research carries a risk of failure. This category solicits proposed research that has a high risk of failure balanced by the potential for high reward. Particularly competitive proposals will be those in which the research is aimed at proof-of-concept or exploratory work with the potential for providing transformative insights, either within the proposed scope or through research supported by follow-on proposals. The justification for this category is that proposals with a high element of risk are often evaluated more critically than proposals with abundant pilot results that set a clear plan for progress. This is particularly the case for proposed projects that involve high levels of stakeholder interactions, that require new instrument or algorithm development, or that address a research question in a manner that challenges established paradigms. Identifying a proposal as high risk provides the ARC with an opportunity to balance the potential of high value outcomes against risk of failure.

5.4. Synthesis and Integration

A necessary partner to process-oriented research is research that focuses on synthesis and integration. While technological and theoretical advances have allowed researchers to develop complex algorithms, design sophisticated instruments, and assemble massive amounts of data, our ability to distill the flow of data and information is increasingly challenged. Furthermore, Arctic researchers are increasingly

recognizing their responsibility to make their products and outcomes impactful, requiring new types of analyses and interpretation. As a result, proposals that focus on synthesis and integration are relevant to all three ARC programs. Successful proposals may include, for example, studies of non-linear responses of the Arctic natural system to physical or biogeochemical drivers, emergent behavior in linked components of the system, meta-analyses of extant results, or policy-oriented context mapping. Proposers should clearly identify how the results of the work will enhance system-level understanding. Synthesis and integration activities can also play a role in program planning that involves exploration of interdisciplinary (e.g., social-ecological) or geographic (e.g., arctic-global) interfaces. These activities may be coupled with a strategic envisioning process (described in Section 5.2.) Synthesis can help to locate key research in policy-making – an important broader impact – thus ensuring that policy decision processes pertaining to the Arctic are grounded in science. It is important to note in this context that policy-relevant research is distinct from advocacy.

5.5. Long-term Perspectives

Many Arctic processes operate on time scales of decades or longer. Sustained observation is important to understanding the changing Arctic system. Understanding these processes may require sustained monitoring and measurement programs that require a commitment longer than the typical award period. At the same time, all NSF-funded research must be placed in the context of evolving research questions. Examples of activities and methodologies deployed in obtaining long-term perspectives include archeological excavations, paleoclimate records, monitored vegetation plots, longitudinal surveys, and ocean mooring arrays. To enhance our capacity to understand system behavior, proposals that focus on long time scales and long-term processes may also involve extended or enhanced simulations, data rescue, archive exploration, or the development of proxies. Long-term perspectives on the Arctic natural and social systems may require developing new technologies, mobilizing citizen science, or enhancing existing monitoring protocols, sites and networks. Proposals that seek long-term perspectives are appropriate in any of the three ARC programs.

6. Supporting Components

6.1. Logistics

Field work logistics is the largest cost within ARC, accounting for between 41% and 57% of expenditures in any given year (based on 2003-2017 data, excluding 2009.) The community survey revealed broad satisfaction with the existing processes and investments. The Arctic logistics office supports projects in every program of the Arctic Sciences Section, from natural and social science programs and platforms to education and outreach activities. There was a strong consensus among survey respondents that the existing permanent field resources (Summit Station, Toolik Station, US Coast Guard Cutter *Healy*) should be maintained, but that no additional permanent installations are needed. A recent NSF OPP Advisory Committee report (available for review in draft at time of writing) also concluded that existing Arctic infrastructure is sufficient at present, particularly when the

fairly new ice-capable *R/V Sikuliaq* is included. (The *Sikuliaq* is part of the OCE rather than OPP research infrastructure.) It should be noted that the *Healy*, a medium-icebreaker, is at mid-life. The Arctic logistics team at NSF should consider means to maintain this capability as the ship approaches the end of her serviceable life.

6.2. Cyberinfrastructure

Data (observational, experimental and model-generated) must be archived and made accessible to create new knowledge. To optimize utility, the data should not only be organized in a clear and logical way, but include active data structuring for analysis, visualization, and manipulation in the cloud. This is largely beyond the current capabilities of most data centers. The research community will benefit from strategies for an enhanced platform for data archiving, and more importantly, data exploration, with the ultimate goal to propel and enable new discoveries. New resources and applications could also make "Big Data" and traditional data sets accessible to and discoverable by Arctic communities and the general public.

Such algorithms can allow the continued automated or semi-automated creation of information. For example, a research project may develop a tool that automatically maps a surface feature such as ice wedges from remote sensing imagery. Instead of just archiving a static petabyte-sized map, the data center could house the tool and the raw data, allowing real time updates (ideally) as new data become available. Furthermore, enhanced capabilities could also allow the user to integrate their own field data or remote sensing data or to query the data in new ways, such as, for example, mapping areas that experienced ice wedge degradation during an extremely warm summer.

A second area of critical importance is the handling of human data. Whether this falls into the category of "Big Data" (such as online surveys or internet data mining) or is obtained through interviews, measurement, or other direct means, protocols must be in place to allow the appropriate dimensions of human data to be queried and integrated while other dimensions, such as identifying characteristics or sensitive information, remain secure. Developing these capabilities is a formidable task but has been documented to some extent in the literature. Indeed, Arctic researchers working with local communities have pioneered many innovative data protocols.

It is recommended that resources be made available through an enhanced and continual cyberinfrastructure funding stream to enable new modes of interaction between data and researchers, as well as other potential users, in order to promote transformative research. This may be in the form of stand-alone projects or as supplements to programmatic funding.

6.3. Education

ARC research success relies on a diverse community of scientists who are supported not just for basic research activities, but for fostering the education and mentoring of undergraduate and graduate

students and postdoctoral fellows. Further, programs that bring together researchers with college and K-12 students could enhance and diversify the scientific workforce of the future, which is crucial to maintain, support and develop research practice and outcomes. ARC should continue to view student mentoring and education as key investments, and to strongly encourage diversity and inclusion throughout the STEM pipeline. Program managers should promote NSF opportunities for students interested in all fields of Arctic research by adopting mechanisms to diversify student participation in ARC research. Finally, financial support for postdoctoral scientists and other early-career researchers is essential for the future of Arctic research and is increasingly challenging to fund in an era of budget limitations. Mechanisms to support students and early career researchers could include specifically targeted programs for these researchers. One example is the recommended ARC Graduate Research Fellowship program.

7. Diversity and Inclusion

ARC can play its part in addressing excellence in diversity and inclusion in activities funded by NSF. Diversity in science refers to cultivating talent through recruitment and retention from a range of disciplines, identities, abilities and backgrounds. Inclusion goes beyond compliance to actively working toward a safe and welcoming culture in the laboratory, field site, conference and institution, a culture that allows a diversity of scientists to shape the future development of their field. An important example of concrete support in this area is the NSF-funded FIELD (Fieldwork Inspiring Expanded Leadership and Diversity) project. ARC, with its support of disciplines that traditionally have low diversity and its large commitment to field research in remote locations, has a special responsibility (and opportunity) to lead by providing resources to foster a diverse and inclusive research community. Programs offering training on diversity and inclusion in any research setting should be expanded, and where appropriate, required. Importantly, resources should be provided to ensure that all members of a field team can directly report misconduct, sexual harassment, and other unsafe behaviors by access to a personal emergency two-way communication device (e.g., satellite phone or inReach.) To fully grow in its science mission, the application of the principles of diversity and inclusion must particularly apply to ARC panels, committees and other bodies formed or supported by ARC that are tasked to provide scientific and administrative guidance to Arctic programs.

8. Community Engagement

In accordance with research directives articulated by the Inuit Circumpolar Council, permanent participants on the Arctic Council, and in accordance with the *NSF Principles for Conducting Research in the Arctic* (2018), community engagement in any research project funded by the ARC should be thoughtful and deliberate. When communities are involved in a research project, best practice suggests that engagement from research design phases through to data collection, analysis, and post-field work evaluation and publication is appropriate. This, however, should be balanced with respect for

community time in planning research that is as yet unfunded. In particular, Arctic communities should be given access to research findings that take place within or near their communities, or which may have a direct impact on their lives or wellbeing. Where appropriate, a community engagement plan should be devised and included in proposals.

When research is taking place on or near current or Indigenous ancestral land there should be particular attention paid to collaboration and engagement. This includes receiving prior and informed consent on all research that takes place in Indigenous territories, and filing research plans with Indigenous leadership. Community priorities and research priorities should be clarified before the research begins. Intensive listening is key to these collaborations; and expectations and objectives of all parties should be clear. Researchers should signal that local knowledge is valued and, where appropriate, should be sought and invited. Where local or Indigenous knowledges are incorporated into a project, there should be clear collaboration principles adhered to from design through publication. This includes equitable resource allocation to all knowledge holders and research participants, including Indigenous knowledge experts. Intellectual property rights for Indigenous knowledges should be respected, as laid out in the United Nations Declarations on the Rights of Indigenous Peoples (UNDRIP 2007).

We also recognize that Indigenous-led research is an important contribution to Arctic science and to ARC. Given this priority, while community-engagement from non-Indigenous researchers is important, it should not act as a substitute for developing research capacity within rural or urban Indigenous Arctic communities, and for supporting and advancing non-Western methodologies and ontologies.