Recommendations for Understanding Arctic System Change:

Report from a Workshop

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Study of Environmental Arctic Change

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Summary of discussions from a workshop held 29 September–1 October 2010 in Seattle, Washington.

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The agenda, participant list, and other workshop information are available at: http://www.arcus.org/search/meetings/2010/understanding-arctic-change

EXECUTIVE SUMMARY: RECOMMENDATIONS FOR UNDERSTANDING ARCTIC SYSTEM CHANGE

Late in calendar year 2010, an Understanding Arctic Change Task Force led a workshop in in Seattle, Washington to develop recommendations to U.S. science agencies on approaches for understanding the arctic system. Support was provided by the National Science Foundation's Arctic Sciences Division with a goal of providing direction for the multi-agency Study for Environmental Arctic Change (SEARCH) and the NSF Arctic System Science (ARCSS) Program. Participants at the meeting were recruited from an extraordinarily diverse spectrum of backgrounds. The discussions in which they engaged were therefore highly interdisciplinary. The workshop agenda, participant list, and other information are available at:
http://www.arcus.org/search/meetings/2010/understanding-arctic-change.

Participants were asked to address two main issues: (1) the need for a set of science questions that represent the pressing scientific needs in 'understanding change', and (2) ideas for approaches, or *how* we might undertake the next generation of science.

Scientists in attendance were instructed to move further afield than traditional disciplinary approaches. They were encouraged wherever possible to identify "big picture" concepts that do not garner traditional attention from researchers. The results of discussions on the pressing science questions and general approaches are included later in the report. This executive summary focuses on some of the most interesting and novel conclusions.

All members were in agreement that the Arctic is undergoing rapid transformation that must be documented, analyzed, and predicted using established tools of environmental and social science. But recent arctic changes have been more striking than anyone would have imagined even 30 years ago, and their rapidity was not predicted by "business-as-usual" science. The global implications of these changes add urgency to the quest for improved understanding. Moreover, the recent changes pervade the arctic system, requiring more than traditional disciplinary science for progress. Arctic research has reached the stage that research strategies must be combined and applied in novel ways.

For example, as logical metaphors for dealing with rapid planetary scale change, the Manhattan Project and the Space Race were mentioned on several occasions. The speed of the ongoing change in the Arctic was often contrasted with the slow, steady pace of traditional science. A strong consensus was that arctic change is winning this particular race. One heartfelt viewpoint among the participants was that bold action is demanded. The following ideas lay furthest from the mainstream:

- The disperse nature of collaborations demanded by the science of arctic change will mean that virtual universities and research centers must be opened and cultivated. These will provide the requisite lines of communication and intellectual support. No new walls, just new linkages. Clearly then, a next generation of "scientific networking" professionals must be educated and recruited for support purposes. These individuals will spend entire careers on maintenance and improvement of the virtual research matrix.

- Arctic change can be viewed as a challenge to both national and international security. As such it should be addressed through scenario studies akin to those applied by the military, which could take the form of "environmental gaming". Modeling is best cast as a means for emphasizing ecological services and global feedbacks. Think-tank activities should be supported to get the ball rolling on the requisite research.

- Strong shifts in the academic structure must occur in order to train young, interdisciplinary researchers focused upon the Arctic as a system. This new crop of talent must be capable of dealing with abrupt environmental transitions. The next generation of researchers must combine a system-scale perspective with consideration of the often-local needs of stakeholders (including planners and responders).

- Science activities should be supported in an cross-agency manner to make the most of available capabilities. Some government institutions specialize in laboratory, process, or field studies, others in remote sensing, big computing, and so forth. The agencies must therefore be teamed more effectively than is now the case in arctic research. Bring them all to the table together. Industries, corporations and local residents must also be involved closely, because they are knowledgeable stakeholders.

- Some funds should be steered away from the standard several-year cycle into two unfamiliar but potentially more productive modes: one very short in turnover (on the order of months) and one much longer than is customary (on the order of a decade).

Much admiration was expressed by the attendees for "skunk works" style operations for large programs—a term borrowed from the aerospace industry to describe a group given a high degree of autonomy and unhampered by bureaucracy, tasked with working on advanced or innovative projects. It is well known that under appropriate circumstances, bureaucracy can be streamlined to enable rather than hinder high-priority research. Several meeting participants expressed their appreciation for private funding sources, which arrive at the university level with a minimum of strings attached, and others noted that the "can-do" attitude of corporate culture should not be eschewed.

Details of possible mechanisms for the next generation of research began to crystallize at the meeting as analogies were discussed, primarily with techniques from the social sciences. For example, the phenomenon of mediated modeling (where different stakeholders and experts are brought together to develop a simulation model) was discussed in the context of how we could better integrate perspectives from industry and local peoples.

As might be expected, objections to some of these less-traditional ideas were raised steadily throughout the meeting and tended to be vocal and eloquent. Objections can be grouped into two major themes: large projects require resources that simply may not be available, and real world problems now unfolding are in danger of disappearing from the "radar screen" if there are major diversions of resources.

There was strong encouragement for a certain amount of indulgence in the outside-the-box thinking. Momentum therefore built over the course of the discussions. There was discernible movement toward the outlook that new approaches are warranted, even demanded, by rapid arctic environmental change.

In contrast to the recommendations for new and potentially high-risk approaches such as those discussed above, there was also support for existing approaches to arctic science and ongoing activities, which provide valuable data and insights. Some workshop participants who felt that our current, organic approach to the study of arctic environmental change is working relatively well —to the extent permitted by the funding base—and may simply require better nourishment in order to flourish. Certainly, new approaches can evolve without undermining the stronger elements of the current research enterprise, and specific actions to be undertaken in the near term are clear.

Retreat-style meetings should be arranged as soon as possible, bringing together key players who can represent all points of view. At early gatherings, particular advances in understanding could be targeted and progress toward these advances could be achieved to the extent possible, while structures and costs could be laid out for broader involvement of the research and stakeholder communities. The potential for "skunkworks" and think-tank approaches should be considered alongside traditional process and measurement-based science. The information generated will be drawn together rapidly into formal, proposal-style documents with clear strategies for entraining participants. The documents will intentionally be given a rich interagency flavor. It is possible that high level, peer reviewed publications can begin to flow immediately from these interactions.

Several peripheral but related concepts were advanced at the workshop in the interest of enhancing research efficiency. It was suggested that a remolding of the established "publish and perish culture" is desirable. The notion here is to incentivize rapid dissemination of results and to develop new approaches that maintaining quality assurance while speeding up access to research results.

The main text of the workshop report, below, begins with background information and rationale for why advances in arctic science are urgently needed. Key research issues are then discussed in a framework of five science questions that cross disciplines and methodologies. Finally, a discussion of recommended approaches captures elements of the preceding summary as well as other points of general agreement from the workshop in areas of scientific methodologies, program management, capacity building, communication, partnerships, and data and information sharing.

BACKGROUND AND RATIONALE: THE DEVELOPMENT OF UNDERSTANDING THE ARCTIC SYSTEM

The concept of arctic system science was initially developed in the 1980's and has matured since then with significant support from U.S. science funding agencies. The overall focus has been to understand how the Arctic functions as an integrated biophysical system, and particularly how it functions as part of the global climate system. Research has targeted specific issues such as:

- Advancing from a component understanding to a system understanding of the Arctic;
- Elucidating the behavior and changes of the arctic system—past, present, and future; and
- Understanding the role of the Arctic as a component of the global system.

As a result of this focus, there has been emphasis on upscaling local findings to the whole system, and on large-scale *scientific* synthesis. Remarkable progress has been made in developing a more holistic understanding of the functioning of the arctic system. Many important questions remain and fundamental research to address these is required. However, certain findings are now unequivocal. The Earth, and particularly the Arctic, is demonstrably changing. We expect that current patterns will continue, leading to a future that is warmer, with higher sea levels, less sea and land ice, and a more energetic hydrological cycle. Uncertainty as to the magnitude, geographic distribution, and rates of these changes remain and further work is needed to assess the potential for abrupt and possibly irreversible change. In addition, a more fundamental integration of socially relevant concerns into the science is needed. This includes the societal need for information to respond to the changing conditions and perceptions, as well as involvement of the social sciences to help define and address key research problems in the context of societal needs.

The need to adapt to a changing climate places some different demands on the research community. Global climate models provide information on large-scale averaged climate patterns. Decision-makers, by contrast, must address how their communities and industries interact with the environment in very specific and local ways: When and where will the fish be? When and where will the land surface be frozen hard enough to operate heavy equipment for mineral exploration and development? How will increased industrial activity interact with natural systems?

Answering any one of these questions will be largely the responsibility of government and industry scientists and decision-makers. Developing the appropriate knowledge and tools for those scientists and managers, however, is a responsibility for the research community. We are being challenged to develop the necessary understanding and technical tools to allow those managers and communities to plan and manage in a rapidly changing environment.

Emerging societal needs require several thrusts in arctic system science:

1. Continued development of **focused research to better understand the climate system**. This includes refined projections of possible future climate patterns and how they will develop as a result of the interacting physical, biological, and human systems. Increased emphasis on smaller spatial and temporal scales (extreme events, regional changes, etc.) is needed in future work.

2. Develop research questions and programs in which **issues are framed in terms of management or decision challenges**. In many instances, this will require fundamental research on issues such as shifting patterns of biotic resource availability (e.g. fish, caribou) and infrastructure development.

3. Develop the **tools for scaling arctic-level patterns down to the local-to-regional level** at which most decision-makers operate. Decision-making and responding to change will occur within specific regions and locales: communities, states, and nations. Doing that planning requires knowing what is likely to happen in those areas. A global or even regional average is of limited value to a local land manager. They need local information. They also need to understand how their decisions will influence the dynamics of the natural and social-ecological systems that they manage.

As arctic science moves into the future, we therefore need to increasingly focus on providing information and insights that will enable societies to respond to the changing Arctic. However, this information must be grounded in solid scientific understanding that is the hallmark of basic research. Basic research is a prerequisite for the applied research that will directly serve society's needs. Moreover, we note that the increasing emphasis on societally relevant applications of basic research is distinct from applied science such as geo-engineering, which is not included in the strategy summarized in this report.

In summary, the arctic research community must expand its mandate by (1) integrating human decisions and actions into our understanding of how natural systems will function and, in doing so, (2) targeting the local scales that directly concern arctic communities, planners and decision-makers. Similarly, in identifying consequences of arctic change for areas beyond the Arctic, at the primary targets should be the impacts of greatest societal importance.

SCIENTIFIC QUESTIONS: FRAMING THE CHALLENGE

For the purposes of defining large-scale thrusts of research programs, we have gathered the collective input from scientists who work at local-to-regional and even global scales, some with ongoing interactions with decision makers, to develop areas for future inquiry.

Based on this input, we pose five scientific questions that we believe should be driving the next phase of arctic system research. These questions are fundamental to understanding the trajectory of the arctic system and are framed in a way that highlights their societal relevance. There was strong agreement at the workshop that the next phase of science should include research that provides information to inform issues faced by decision-makers at the local, regional, or national levels. These questions also provide a means to integrate observational science (such as the Arctic Observing Network [AON], etc.), understanding science (modeling, reanalysis, etc.), and 'responding to change' activities.

We divide the questions into three subgroups. The first two questions focus on the nature and predictability of the arctic system. The third and fourth questions focus on interfaces between components of the arctic system, and between the arctic and global system. The last question focuses on changes in the cryosphere—we target the cryosphere specifically because it is a defining element of the Arctic and because many system changes are driven directly by changes in the cryosphere. These science questions also align with existing science plans and recommendations, which are referenced below where appropriate.

1. How Predictable are Different Aspects of the Arctic System, and How Can Improved Understanding of Predictability Facilitate Planning, Mitigation, and Adaptation?

To meet the needs of planners, policymakers, and communities challenged with adapting to and mitigating arctic change, there must be an understanding of, and ultimately improvements in, predictability of these changes over various time and geographic scales. This requires determination of (1) the inherent and realizable predictability in various aspects of the arctic system on various timescales, (2) information on what planners and decision-makers require for predictions to be “useful”, and (3) actual predictions, projections, or scenarios of the arctic system that meet these requirements. The scientific community must communicate the current predictive capabilities in various domains and define any uncertainties in clear and useful ways. Due to the urgency of many arctic issues, it is not feasible to wait for an exhaustive body of knowledge before translating the science into information useful for society

Our current predictive ability at the large-scale (global/regional) is more advanced than at the smaller (localized) scales, which are relevant for planning. "Downscaling" global predictions to local areas is hence a key area of future research.

Examples of sub-questions include:

- What do users, planners, policymakers, and other arctic stakeholders require for predictions to be useful?
- What predictability is possible in various aspects of the arctic system, and over what timescales?
- How can we better include human dimensions in predictive models?
- Are thresholds and extreme events predictable to the extent that the information can be used for planning and adaptation?
- What are the optimal ways for conveying predictive information, given the uncertainties that will be inherent in predictions?

2. What are the Arctic System's Tipping Points: the Abrupt Changes that are Most Consequential for Ecosystems and Humans?

There is evidence of thresholds in the Arctic system that, once crossed, may make the system vulnerable to feedbacks that initiate abrupt system changes. Extreme events (e.g., hydrologic anomalies such as droughts and floods, extreme melt anomalies, ocean mixing events) may trigger the crossing of such thresholds. While many of these thresholds are unknown, extreme events in the Arctic are also poorly observed and documented. Assessment of thresholds, triggers and abrupt changes should focus on processes most consequential for ecosystems and humans.

Tipping points may also result from small changes that result in a system's move to a new equilibrium state ("The straw that breaks the camel's back"). Whether or not the Arctic is presently near a tipping point has been the subject of recent scientific debate. In the context of this report, the assessment of tipping points and abrupt changes should consider changes that are most consequential for ecosystems and humans, although such an evaluation is difficult since the potential impacts of different types of change are presently not known.

Example sub-questions include:

- What are the roles of extreme events as triggers for abrupt changes?
- What are the most consequential thresholds? What are the processes by which they are reached, and can we quantify them? How irreversible (over the span of human lifetimes) are changes that will occur when thresholds are passed?
- To what extent does the passing of a threshold in the physical system (sea ice, atmosphere, permafrost) lead to abrupt changes in arctic ecosystems?
- Can (and to what extent do) abrupt changes in biophysical systems lead to abrupt changes in social systems (e.g., transportation, industries, ability of certain human land uses)? How do human actions or reactions feedback to the biophysical system?
- What are the positive feedbacks that can drive rapid changes in ecosystems?

Answering these questions will require the integration of models, long-term sustained observations, and experiments. Integration with the paleoecological and paleoclimatic community as well as the ecological and various social sciences will be necessary for addressing questions about long-term system dynamics and the feedbacks within them.

3. How Will the Critical Intersections Between Human and Natural Systems in the Arctic Change Over the Next Several Decades?

One way to address relevant intersections between human and natural systems is through what are called *ecosystem services*—phenomena or features of ecosystem dynamics that humans use directly and which can have financial value. Food, industry, water, and cultural value are some of the foci of these intersections. Examples include marine transportation and development; terrestrial industrial infrastructure such as roads, mines, fisheries, hydropower, and wildlife/subsistence. In the case of fisheries, for example, human and environmental drivers interact to produce variations that impact a major industry and food source.

Another way to capture the intersection between human and natural systems is through the concepts of *vulnerability* and *risk*. Natural systems involve processes (e.g., floods, receding sea ice, fires) that pose hazards to exposed human systems (e.g., communities, buildings, infrastructure). We need scenarios to address possible human vulnerabilities and responses. Scenarios are employed throughout industry for planning and underpin many assessments of climate change. In contrast, they are currently not employed in any significant fashion within the arctic research community, but hold significant promise in providing a mechanism to synthesize and compare output from a range of models (heuristic, analytic, numerical) and knowledge systems.

Example sub-questions include:

- How will industrial activity in the Arctic change in response to altered climate and thermal regimes?
- How will changing patterns of climate and marine activity (e.g., fishing, shipping, mineral extraction, tourism) alter marine food webs and productivity in the Arctic? (A parallel question holds for the terrestrial environment.)
- What are the interactions between the Arctic Ocean and the atmosphere and what are the implications for hazards, resource extraction, subsistence etc.?
- What are the global to local drivers of social change and how will this affect interactions of humans and the arctic environment (e.g., greater demand on ecosystem services that are themselves changing, increased human vulnerability to physical hazards)?
- How are the rapid social changes already underway in the Arctic (e.g., migration, health issues such as suicide and alcohol, isolation, aging demographics, government policies, economic development, changes in information technology) changing the interaction of human communities with climate-driven changes in natural systems (risks, vulnerability, and adaptive responses)?

4. What are the Critical Linkages Between the Arctic System and the Global System?

Lower latitude processes are coupled to the arctic system at all levels—geophysical, geochemical, ecological, social, and political. Examples are plentiful. The ocean transports heat energy and nutrients into the central Arctic basin. Water ice and greenhouse-gas-containing clathrate deposits may be destabilized as a result of warming, while ecosystems may shift geographically, resulting in potential ecosystem reorganization. Atmospheric carbon dioxide is responsible for not only the bulk of global warming but also the rapid acidification of arctic seawater. The extent to which the Arctic Ocean can take up carbon dioxide has global implications, and further determines cloud properties and the fate of air pollutants. Atmospheric and riverine inputs to terrestrial ecosystems influence atmospheric composition, humidity, carbon cycling, and permafrost degradation.

There are feedbacks that affect lower and middle latitudes through ice, snow, aerosol, cloud and vegetation reflectivities and greenhouse gases. Known or suspected feedbacks have societally relevant consequences such as species migration, the migration of disease vectors, changes in the hydrological cycle (since they affect water resources), transportation on or through sea ice, and a variety of national and human security issues. Transportation through the Northwest passages and Nothern Sea Route may have global economic, trade, and security implications, as well as a potential vector for invasive species to the marine ecosystem. Mineral extraction from areas currently still covered by sea ice are already fostering international tension among Arctic nations regarding claims of sovereignty, economic influence, and competition. Such geopolitical issues will impact local economic opportunities, challenges, and risks. In turn, local human concerns will need to percolate upward to national and international bodies if they require supra-local institutions and influence to be addressed adequately.

Examples of sub-questions include:

- How will changes in the Arctic environment affect the diversity and value of global ecosystem services?
- What portion of the total in the soil carbon will become available for biogeochemical transformation, e.g., conversion to methane?
- How much will the salinity and acidity of the ocean change and how will these changes affect the production and biodiversity of the global oceans?
- How do the global forcings express themselves differently at local levels?
- Will sea-level rise lead to altered pathways of pollutants into and within the Arctic system?

5. How will Changes in the Cryosphere Drive Changes the Economic, Social, and Environmental Components of the Arctic System?

Shrinking sea ice extent, retreating glaciers, thawing permafrost and changes in snow distribution will have strong economic, social and environmental consequences. Assessment of these consequences will require credible projections of the cryospheric changes. Such projections, in turn, require improved understanding of the key mechanisms responsible for current and future changes in sea ice, the ice sheets and glaciers, and frozen ground.

Local knowledge of vulnerabilities to sea level rise and the history of sea level and subsidence at the *local* scale can complement model output. Given considerable misconceptions about local and regional expression of global sea level rise, communication of key findings to stakeholders is very important.

On the *regional* level, there is great potential for better synthesis of available information on likely scenarios (e.g., changes in sea ice patterns) from regional integrated assessments as well as climate and earth system model output, paleo-analogs (such as the mid-Holocene warm period) and place-based knowledge of patterns of variability and processes.

On the *national and global* scales, addressing the impacts of cryospheric change requires participation by stakeholders, social scientists and physical scientists. The National Climate Assessment is an example of an approach that assembles multiple stakeholders and provides funding for workshops and writing teams, and can lead to new and directly fundable research activities. Such an approach may be useful for the topic at hand, in which the global impacts of cryospheric change are given enhanced attention and made relevant to ongoing decision making.

Examples of sub-questions include:

- How will changes in the cryosphere affect the rate of global sea level rise over coming decades?
- What determines the variability of the discharge from glaciers, ice caps and the Greenland ice sheet?
- How will various cryospheric changes interact (e.g., freshwater discharge from the ice sheets, the trajectory of sea ice, changes in permafrost)?
- How will cryospheric changes affect water supplies and other human needs?
- What are the local, regional and global vulnerabilities to cryospheric change, including sea level rise?
- How will public perceptions and policies regarding the arctic and global environments be affected by cryospheric changes?

THE WAY FORWARD: RECOMMENDED APPROACHES AND ACTIVITIES

1. Scientific Approaches

In addition to identifying key science questions, workshop participants discussed approaches for *how* to meet emerging scientific challenges.

Workshop participants stressed that any future activity or program must be organized around a well-framed targeted question or set of questions, rather than broad high-level themes, thus providing a clear nexus around which to organize efforts. These could be at the level of the sub-questions summarized in the previous section, or could be more targeted, for example, "What will the Arctic look like if we have an ice-free summer in 2025?" Different science funding agencies may choose to focus on different questions, based on their missions and priorities. In addition, we have reached a point where human dimensions research must be fully integrated into a modern arctic science program. Stakeholder issues should help shape the research questions from the beginning.

Workshop participants recommended several specific approaches and activities, summarized below that are applicable irrespective of specific science questions.

Utilize Place-Based Science – Place-based science would focus on "synthesis sites" where studies are co-located and data is synthesized together. Each place is a center (or “bull’s eye”) that naturally creates intersections among disciplines and system components. The model of discrete projects would be deemphasized in favor of managing a site as an evolving mix of core and linked projects targeting a key question or problem of local, regional and/or global importance. Projects would link together through a shared focus and collaboration on the site and cross-project synthesis. Incorporation of local and indigenous knowledge will be critical for undertaking relevant place-based research. Field stations such as the Toolik Field Station in Alaska have long acted as nexuses for inter-project collaboration, even when that was an “unintended consequence” of the essential need to provide housing in a remote area.

This place-based approach has proven to be valuable and sometimes transformative as way of organizing science and provides an easy avenue for collaborations between funding agencies. To more actively build coordination as a target of the initiative, viable proposals would likely require a year of planning effort including face-to-face meetings to organize an interdisciplinary team of scientists, consult with members of the community involved, and secure agreement on the specific problem to be addressed at the site.

Inter- or Transdisciplinary Research – Research that spans disciplines, especially research crossing the physical, biological and social science boundaries, remains a major challenge. Frameworks such as ecosystem services or local and traditional knowledge can help advance research in this direction, as can various approaches presented elsewhere in this section.

Short-term, Intensive Science Retreats **–** To supplement longer-term science efforts, workshop participants recommended short-term science activities in the model of a 1-2 week "think-tank" retreat or workshop, with the aim to produce specific products.

Focus on Down-Scaled Predictions and Projections - While efforts to improve our understanding of arctic change can include a variety of scientific approaches, societally relevant information will require a focus on projections, predictions, and scenarios of future states at regional and local scales. In addition, spatially explicit models would bring people and ecosystems together at various scales.

Synthesis Activities – Although efforts toward understanding should allow for projects to fill in key observational gaps as part of an integrated program, priority should be given to synthesis activities, and some science questions could be approached with a 'no new data collection' rule. Coordinated global and regional model experiments, especially experiments utilizing ensembles of different models, could be useful vehicles for synthesis. To date, comparative model experiments addressing scientific problems have been generally under-exploited in arctic research.

Online sharing and public engagement - Online sharing and citizen science can result in significant contributions, similar to advances made in the astronomy sector in encouraging participation by citizen scientists and experts. Impacts of cryospheric change on greenhouse gas concentrations (permafrost thaw) and aerosols and hence radiative forcing provide a promising focus for investigation and would benefit from integrative workshops that bring together theoreticians, large-scale modelers, and emission data sets to explore revised scenarios on greenhouse gas forcing and recommend new modeling initiatives.

Ideally, as indicated in the Executive Summary, there would be a mix of longer-term activities (including place-based research) and shorter intensive efforts.

2. Program Management Recommendations

The current funding mode is incongruent with today's need for a coordinated, adaptive, and integrative program.

A spectrum of funding mechanisms is needed. On the one hand, funding agencies will need to support small, high-risk, activities, accepting that a percentage of these efforts will fail. Such projects need fast and more responsive funding mechanisms.

On the other hand, to create more comprehensive and synergistic initiatives, projects and programs need longer-term funding (i.e., longer the standard 3-year project duration), as well as joint agency funding. There is also a need for creative mechanisms for phasing participants in and out of a long-term funded activity, thereby enabling a dynamic optimization of the participant base.

In addition, the standard written review/panel review process is not the best model for this kind of initiative. Agencies should consider jointly-reviewed or jointly 'owned' process, where a steering committee or representatives of programs are involved in guiding the program. For example, a Steering Committee, working with a funding agency, could select a priority science question(s), the agency(ies) could release a call for 2-page pre-proposals, a science steering committee could select the most relevant pre-proposals with the best ideas, and the PIs of the selected pre-proposals could meet in person for 2-3 days to develop a full proposal that integrates the ideas.

Finally, programs need to provide sufficient support for staffing and leadership of efforts and cannot rely on volunteer time. They need to provide for mechanisms for direct collaboration (including international collaboration) between projects, and between funding agencies.

3. Capacity-Building

A strong theme that emerged from the workshop was the need for skill and knowledge exchange as the scientific community builds its capacity. To achieve major progress in understanding arctic change, we need to amplify human resources and teambuilding simultaneously and devote sufficient resources to do so. Recommended activities to address this problem include:

- Annual science meetings – community-wide 'all-hands' meetings and/or meetings for groups of PIs and projects
- Interdisciplinary training via seminars and webinars
- Visiting scientist program for knowledge exchange (visits of a week to a year)
- Summer schools focused on a key science question(s)
- An organized online network of experts accessible for information and guidance
- Funding for stipends for local observers and experts, particularly for individuals who can bridge scientific and traditional/indigenous knowledge systems
- Incubation grants to build connections to social science and human dimensions communities

4. Communication

Communication and outreach activities at a variety of levels, with sufficient funding support and staffing, are a priority for any understanding arctic change program.

The highest priority communication need is to develop ongoing networks and exchanges to/from the public (e.g., key stakeholders) and decision-makers, in order to help define specific research activities and convey scientific information back to decision-makers. The scientific community needs to clearly articulate what we know, along with showing more clearly *how* we know that, and our levels of uncertainty regarding different future projections. Likewise, the research community needs to hear from decision-makers what information they need to prepare for and manage a rapidly changing environment. Two-way communication throughout the scientific process is essential. With regard to the broader audience – the public – scientists should listen not because the public is necessarily "right" about sea ice or other topics, but because the scientific information might be communicated more effectively when we understand what people already believe, and why.

There is also a need for improved information-sharing between scientists and resource managers. This could be described as a current institutional communications barrier that can be overcome through, for example, including agency scientists in research teams.

5. Partnerships and Coordination

There is an enormous amount of talent, resources, and activities that can be built on through improved partnerships amongst agencies, programs, and scientific communities.

Improved coordination across U. S. agencies (specifically NSF, NOAA, DOE, and NASA) is critical, through joint funding initiatives, formal agreements, or other strategic partnerships. This could be facilitated by the newly re-organized Interagency Arctic Research Policy Committee (IARPC).

Coordination with non-arctic science communities is also essential. Partnerships with global modeling, Earth system, and paleoclimate communities will be required for progress, including national centers such as NCAR, GFDL and GISS. In addition, given the emphasis on nonlinear systems, it would be advisable to build partnerships with research institutes that explore complex systems dynamics and nonlinearity.

Improved ties with social sciences are needed both to enhance human components in modeling and predictive exercises or scenarios, and to systematically consider the societal implications of research results. These efforts can draw on partnerships with established human dimensions researchers focused on non-arctic systems.

Strong connections to established observational programs, including the Arctic Observing Network (AON), the National Environmental Observing Network (NEON), and Long-Term Ecological Research (LTER) networks, will help develop observational networks responsive to modeling needs.

6. Data and Information Sharing

Data management cannot be an afterthought in the scientific process. It must be an integral part of science. Improving our understanding of arctic system change and its impacts demands a culture of open and collaborative data and information sharing. Strong emphasis on documentation and adherence to basic standards will go a long way towards promoting sharing, data integration, and interdisciplinary reuse.

NEXT STEPS

The Understanding Arctic Change Workshop brought together a diverse set of scientific perspectives for three days of far-ranging discussions on the next stage of understanding arctic change science. Participants developed five crosscutting science questions and recommendations for what is needed to implement the science. The recommendations include some of the usual methods for doing science, but also delve into creative, non-traditional approaches, as well as a formulation of science needs that is more cognizant of societal needs. The SEARCH program and funding agencies are encouraged to work with the broader arctic science community and stakeholders to support the types of activities that are summarized in this report. Only a concerted, organized effort to understand arctic change will provide us the knowledge we need to predict the changes in the Arctic, and how they will impact ecosystems and societies outside the North.