Opportunities and Challenges in

ARCTIC SYSTEM SYNTHESIS

A Consensus Report from the Arctic Research Community

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PREFACE

In November 2016 and again in April 2017, community workshops were convened on the subject of Synthesis Studies of the Pan-Arctic/Earth System. These workshops were devoted to exploring approaches that could be used to uncover emergent properties of the Arctic system operating as a unique but integral part of the larger Earth system. The workshops were topical in nature, with each featuring a single multidimensional research challenge designed to provide a window into understanding processes that define and function within the Arctic system and to provoke new ideas for conceptualizing the Arctic and its studying connections to the Earth System. One workshop focused on multiple "currencies" that link the Arctic climate and environment—geophysical entities such as water, energy, carbon, and nutrients with quantifiable properties—and how they interact to produce and illuminate systems-level behaviors. The other was devoted to the causes and impacts of climate-related, as well as other, extreme events on the Arctic system and beyond.

As the title of this report suggests, the workshops emphasized the notion of executing synthesis: understanding the behaviors and interactions of the whole system that are greater than the sum of the individual parts. In addition to presentations and informational exchanges among the workshop attendees, the effort has produced this report delivered to the National Science Foundation, to be followed by an excerpt published as a peer-reviewed publication. Both documents have two aims: to first highlight key gaps and challenges needing to be addressed to achieve a more complete systems-level understanding than is currently in hand, and next to identify opportunities for new research paths.

The workshops were constituted as 2.5-day events. The first took place at the Advanced Science Research Center of the City University of New York, from November 12 to 14, 2016, and titled "Extreme Events in Contemporary and Future Timeframes." The second was in Washington, DC, at the offices of the Arctic Research Consortium of the United States (ARCUS) from April 17 to 19, 2017, on "System-Level Currencies (Energy, Water, Carbon and Nutrients) and Their Role in an Evolving Arctic." A writing workshop, integrating the presentation materials and discussions at the first two workshops, took place on October 5–6, 2017, in New York City. Near the final stage of publication, the report was open to public review, from which proposed modifications were assessed by the convening committee and adopted, as appropriate.

The more than 40 attendees were drawn from across several relevant disciplinary domains, and included participants with experience in pursuing systems-level and integrative research. Perspectives offering insights through simulation, data-rich approaches, and field experiments from both the biogeophysical and social sciences were also articulated. The expertise represented in the two meetings included:

- Atmospheric Dynamics/Arctic Climate
- Permafrost Change and Dynamics
- Ocean and Sea Ice (Physics, Chemistry, Biology)
- Social Systems
- Ice Sheets and Glaciers
- Ecosystems (Land-Based)
- Public Policy and Science Diplomacy
- Hydrology
- Science Communication and Education

The workshops also included a cross section of career stages within the Arctic research community—graduate students, junior faculty, and mid and senior career-level faculty. The private sector was also represented. Through formal presentations in plenary, plus interactive breakout sessions and informal exchanges throughout each event, the collective input from the assembled community is represented in this report.

Building on its objective to review some of the major systems research developments that came to light during the two-workshop dialogues, the report goes on to provide specific recommendations to agency program managers, policymakers, and the public and private sectors on future research opportunities and investments in the theoretical and applied aspects of Arctic system science. The issue is made all the more timely by rapid changes in the Arctic's climate, biogeochemistry, and socioeconomic systems and in the broader context of global change in the Anthropocene. Participants in the two events provide in this report their collective advice and consensus on future research investments—both thematically and institutionally—that they see as necessary to stimulate breakthroughs in this arena.

— THE ORGANIZING COMMITTEE
Charles Vörösmarty, Michael Rawlins, Larry Hinzman, Jennifer Francis, Mark Serreze, Anna Liljedahl, Kyle McDonald, Michael Piasecki, and Robert Rich

EXECUTIVE SUMMARY AND CHIEF FINDINGS

Chapter 1. Introduction: Why Study the Arctic and the Arctic as a System?

This report presents arguments for new science in the Arctic, recognizing that the High North has unique strategic importance to the nation and to the world—in terms of its resource base and economy, sociopolitical dimensions, and, of course, as a critical throttle point for global change. Improved understanding will therefore be essential in order to manage this important element of the planet. The research community is poised for significant growth in understanding the role of the Arctic as a system, with that position afforded by recent progress in understanding the Arctic through the interplay of its physical, biological, chemical, and social science components.

The community has made great strides using many fundamental technical resources already in existence, including key measurements from Arctic observatories as well as advances in modeling approaches and analysis tools. And, over the last decade, Arctic researchers have begun to adopt into their studies what traditionally have been isolated approaches and under-utilized data sets, including those from global satellite observations, buoys and moorings, permanent and ephemeral meteorological stations, and isolated process studies that advance knowledge of system mechanics and dynamics.

Casting this as a systems-level challenge has the benefit of mobilizing otherwise disparate resources for improved knowledge and better decision-making. These efforts toward higher-level syntheses and data fusion will stimulate new technologies and analyses, which will enable more science-based input to policy dialogues. The result will be improved decision-making regarding societal responses.

The Arctic system challenge is an ideal example of the need for transdisciplinary, multiscale, natural-human system research. If appropriately cast, it provides an analysis framework to better understand and forecast Arctic change, which underpins Navigating the New Arctic (NNA), one of NSF's recently announced 10 Big Ideas (NSF 2018). Furthermore, Arctic system analysis and NNA fit aptly into the realm of another of the *Big Ideas*, namely Convergence Research, where a well-focused research challenge cannot be met without synergy across multiple disciplinary perspectives using the respective state-of-the-art concepts, technologies, and nomenclatures.

Chief Recommendations

A more comprehensive understanding of the sources, scope, and impact of Arctic-system change—and its impact on the global system, grounded within the Convergence and NNA framing of NSF's 10 Big Ideas, will require:

- A revitalized and deepened national commitment to a coherent program of systems-level research, by its very nature interdisciplinary and capable of accelerating the development of state-of-the-art experimentation, observatories, data processing, and simulation modeling; and
- A coordinated effort engaging a broad cross section of Arctic researchers, policymakers, practitioners, and Indigenous stakeholders to identify, requisition, interpret, and act upon the systems-level knowledge that will be necessary to effectively adapt to and potentially attenuate the many interconnected impacts of Arctic system change.

Chapter 2. Currencies: Unifying the Arctic System

The *currencies* of water, biogeochemical constituents, and energy define key linkages across the Arctic land, atmosphere, and ocean domains. The stocks and transfers of these currencies are influenced by the strong seasonality which defines the Arctic system. Its cyclical "green-up," for instance, is closely associated with the exchanges of water and carbon between the land and atmosphere and the seasonal cycle in ocean photosynthesis and primary production is linked to the appearance and disappearance of sea ice. Extreme cold across the Arctic has produced legacies in currency structure and function that reflect earlier physical, chemical, or biological states and activity. A unique aspect of the polar regions is the long cold season, which repeated over millennia have produced legacies in currency stocks, structure, and function that reflect earlier physical, chemical, or biological states and activity. The warming of the Arctic is now releasing these stocks of old currencies, including freshwater lost from melting ice sheets and mountain glaciers or old carbon from thawing permafrost.

Arctic system biogeochemical currencies are dynamic and changing rapidly. One example is how recent permafrost thaw is transforming soil-borne carbon from a frozen and more-or-less biotically inert form into more mobile carbon dioxide and methane that enters the modern atmosphere. Through the prism of permafrost thaw, global climate change thus passes its impact on to the Arctic system through links to altered land surface energy budgets, local geomorphological changes, and legacy effects of carbon stocks sequestered long ago. This serves as a convenient illustration of how currency exchanges amplify and/or dampen system structure and function.

This concept is also demonstrated through environmental changes involving climate warming, glacier loss, and hydrological cycle intensification. The geology and geomorphology of the region—the organization of its landscapes, coastlines, and ocean basins—exerts a fundamental control on the storage, movement, and interactions among the currencies. Unique characteristics of terrestrial watersheds such as soil carbon accumulation, disturbance history, and barrier island geomorphology influence energy and matter transported from the atmosphere to the land and ultimately into the Arctic Ocean. Community-based efforts have advanced our understanding of interactions among water and energy, biogeochemical, and other currencies, and how they are changing in space and time. New lines of inquiry that leverage well-designed field studies, state-of-the-art modeling, and emerging remote-sensing tools are needed to better characterize currency behavior in a full-system context. Addressing research challenges in how currencies become activated and inactivated, the fate of legacy effects from earlier periods, their roles in amplifying and/or dampening other processes, and the myriad interactions with geomorphological controls will ultimately foster a more complete systems-level understanding than is currently available.

Chief Recommendations

To more fully quantify the stocks and fluxes of key currencies, assess their interactions, and predict their evolution within the Arctic system, new synthesis-based research is needed to:

- Establish integrated databases of multi-currency measurements, derived from observatories and field campaigns;
- Advance process modeling to understand how climate forcing and landscape structure interact and to define energy, water, and other mass flows through the Arctic system; and
- Provide theme-based, currency-related research opportunities, for example, how currencies are independently or jointly activated and inactivated, how legacy currency behaviors inform modern system changes, and how currencies amplify or dampen system perturbations.

Chapter 3. Extremes in the Arctic System: Sources, Impacts, and Reverberations into the Earth System

In the physical sciences, an extreme event is typically defined as a phenomenon that is statistically rare, like those documented in records of daily precipitation, surface air temperatures, central pressure in cyclones, or peak river discharges that fall, for example, in the top or bottom 1% of the statistical distribution of all events. Extremes in the biological or ecological realms may be more difficult to define in a statistical sense but in general can be identified as events that clearly stand out from past experience—a massive caribou die-off, for instance. Some such events may last but a day or week while others might persist for a season or even longer. There is growing evidence that extreme events are becoming more common in the Arctic, in part because regime shifts and system pre-conditioning can increase the likelihood of extreme events. In addition, there is increasing recognition that extreme events that develop in one realm can cascade and reverberate throughout the Arctic system. For example, as sea ice cover thins more generally, an anomalous atmospheric or oceanic event can more easily initiate an extreme reduction in summer ice extent, in turn affecting phytoplankton blooms, which can then subsequently affect consumers up the food chain.

Extreme events in the Arctic system can originate in the region itself—or find their origins well outside. For example, atmospheric rivers giving rise to extreme precipitation events can be traced back to the tropical Atlantic. In other cases, the relationship may be two-way—while Arctic amplification is at least in part driven by atmospheric heat transport into the region, Arctic warming may in turn affect the polar jet stream, leading to extreme weather in the lower latitudes. Some components of the Arctic system may dampen responses to an extreme event, a phenomenon sometimes referred to as resilience, while others prove to be more sensitive. Understanding extreme events and their impacts bears not only on the ecology and peoples of the Arctic, but also on the global investment community, which requires a careful analysis of the risks associated with anticipated business activities, such as expanded oil and natural gas production, commercial shipping, and tourism.

Chief Recommendations

To better detect extremes, attribute their genesis, and assess their impacts, efforts are needed to:

- Establish long-term baseline data sets to monitor and detect extreme events in the geophysical, biotic, and human components of the Arctic system;
- Enable advanced methodologies to observationally assess the cascading effects of extremes throughout the system;
- Develop system models of sufficient temporal and spatial resolution to understand links between extreme events, preconditioning, and regime shifts in the Arctic system;
- Unify observational and modeling approaches to improve forecasting of extreme events; and
- Formulate integrated risk and assessment models that evaluate the impact of extreme events on social systems, ecology and economic development.

Chapter 4. Approaches to Synthesis

Change is essentially a universal constant across all components of the Arctic system, and in many cases, changes in one component typically affect many others. Understanding the evolving high latitudes requires synthetic approaches that incorporate not only local processes but also interconnections among the larger Arctic system and other parts of the Earth system. This requires synthetic approaches and data sets that can be used to interpret, understand, and forecast Arctic change as it evolves and then reverberates through the Arctic system and beyond.

Current approaches reflect important realities about the Arctic system: its processes are complex and nonlinear; data sets characterizing the system are proliferating; disciplinary research is today's norm; and demands for policy-relevant knowledge are growing. Varying degrees of success in elucidating the interwoven changes characterizing the modern cryosphere have been achieved through several different approaches to synthesis, including the use of observatory data, sustained field campaigns, remote-sensing products, and models of varying sophistication (from idealized to full-scale Earth system models).

In many ways, however, relatively little is still known about how the Arctic operates as a system, in large part because many studies are too narrowly focused spatially or temporally, are based on pre-warming conditions, and/or address a limited number of processes. To avoid the fragmentation characterizing much of today's Arctic domain research, this report highlights the necessity of focusing the community on specific systems-level approaches and targets.

Chief Recommendations

Building on a history of mostly disciplinary, localized, and individual process-based research, fundamental new systems-level research could be executed to:

- Promote studies that capitalize on a productive interplay between models and integrated, systems-level observations (i.e., in situ measurements, controlled experiments, and reanalyses) cast using linked inductive and deductive approaches and with an eye toward facilitating model calibration and validation through appropriately scaled observatories;
- Adapt or develop a broad spectrum of models with various levels of sophistication—from reduced complexity to full-system models; and
- Establish a suite of coordinated systems-level studies, to complement digital simulation per se, including heuristic (thought-experiment) approaches, benchmark studies based on literature reviews, budget analyses of key currencies, and syntheses of disparate data.

Chapter 5. Systems Science Supporting Policy and Management

Understanding the implications of Arctic system changes should not be restricted to the domain of basic science because they reverberate into many societally relevant arenas: damage to civil infrastructure due to permafrost degradation, reduction in ice-dependent transportation routes over land, coastal infrastructure battered by waves, northward migration of pathogens and vectors affecting human health, disruption of marine and terrestrial food webs, and shifts in large-scale oceanic and atmospheric circulation patterns. Fires and smoke affect infrastructure, permafrost dynamics, and the terrestrial carbon cycle, as well as representing the loss of habitat for land-based species, including those upon which traditional harvesting depends. There will also be many positive effects of a changing Arctic domain—access to new trans-Arctic ocean shipping routes, resource extraction, and new fisheries—but those benefits are likely to be accompanied by a wide variety of costly, negative impacts that will interfere with human activities and undermine economic development across the region.

Because human actions are driven by exigency and immediacy, investments to protect future generations can be significantly delayed, despite warnings that we may imminently be moving past a point of no return. Additional impediments involve complex and inertia-laden bureaucracies, from which messages to the research community become difficult to coordinate. One of these barriers is the tendency of stakeholders to ignore or even be unaware of relevant scientifically grounded information. The chances that decision-makers will absorb and act on scientific information increase when they actively seek data that are focused clearly on their interests and made relevant to constituencies that ultimately fund the research. Identifying and filling key gaps in science and technology readiness today—one motivation for this report—helps to forestall delays in acquiring policy-actionable knowledge upon which future adaptation strategies depend.

This requires open dialogue and co-design of a shared research agenda. An alliance of natural and social scientists, decision-makers, and the private sector will be needed, working together through a co-design process for policy and environmental management. In the context of systems-informed policy design, science diplomacy takes on an important role. It is an holistic process that contributes to informed decision-making to balance national interests and common international interests. Integrated with biogeophysical data, policy and governance records define the evidence that ultimately will be used to identify decision options; for example, the 2017 Agreement on Enhancing International Arctic Scientific Cooperation.

Chief Recommendations

A purposefully designed process will be necessary to adequately translate the emerging scientific knowledge base into the policy and management domains by:

- Creating a co-design process that unites Arctic systems researchers with decision-makers and practitioners in identifying and evaluating options for action—a process that recognizes fundamentally that human decisions made today can have lasting and far-reaching impacts on the Arctic as a system; and
- Placing the results of the co-design process into a science diplomacy framework so that all parties can evaluate the impacts and effectiveness of individual and joint decisions regarding the future trajectory of the Arctic.

Chapter 6. Programmatic Needs

Given the broad and cross-cutting nature of the Arctic systems research challenge, we propose creation of an Arctic Systems Collaboratory, a meeting ground for transdisciplinary research and policy engagement intended to produce holistic, systems-level understanding. Such a collaboratory will necessarily involve the active involvement of a broad cross section of the Arctic research community, combined with a sufficient, yet minimal, central coordination to assure progress is as rapid and efficient as possible.

Key design criteria for a successful collaboratory include the formulation of a clear and shared integrating goal, sufficient financial resources, an efficient knowledge transfer mechanism, virtual or face-to-face meeting grounds, and skilled administrative support. Such a structure better meets the historical challenges of a less holistic programmatic vision by including: team diversity and inclusion; coordination across large-scale, multi-institutional teams; alignment and persistence of goals; accommodation of an evolving participatory group; overcoming geographic dispersion across teams; and coping with a high level of task interdependence.

Chief Recommendations

The anticipated, major outcomes of an Arctic Systems Collaboratory can be cast as a set of recommendations, through:

- Creation of a durable partnership of the Arctic research community, dedicated to promoting cross-disciplinary and systems-level research;
- A shared and co-designed systems science research agenda, involving the inputs of basic and applied researchers, policy experts, indigenous peoples and other stakeholders, educators, and science communicators;
- Supporting infrastructure and operations, with an appropriately centralized project management structure, practical means to ensure continual community-building within the collaboratory, as well as shared data, IT, and other technical resources; and
- Programs for broadening engagement, including those forwarding Arctic systems science, education and outreach, as well as interactions with stakeholders within the Arctic and globally.