Opportunities and Challenges in

ARCTIC SYSTEM SYNTHESIS

A Consensus Report from the Arctic Research Community

Opportunities and Challenges in

ARCTIC SYSTEM SYNTHESIS

A Consensus Report from the Arctic Research Community

ACKNOWLEDGMENTS

The U.S. National Science Foundation's Office of Polar Programs' Arctic Systems Science Program (Grant PLR1455690), under the Geosciences Directorate, supported both scientific workshops, the subsequent writing team meeting, and production of this document. We acknowledge the Advanced Science Research Center (ASRC) of the Graduate Center at CUNY for logistical support. We also thank both the ASRC and the Arctic Research Consortium of the United States (ARCUS) for providing meeting space. Initial editing was provided by Rick Firstman. Additional editing as well as design services were provided by Ellen Kappel and Johanna Adams of Geosciences Professional Services Inc.

CONTENTS

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.

CHAPTER 1. INTRODUCTION

Why Study the Arctic and the Arctic as a System?

This report presents a call for new science in the Arctic, recognizing that the region has strategic importance to the nation and to the world, not only in terms of its geopolitical dimensions and natural resources, but also as a critical throttle point for global environmental change. Improved understanding will be essential to manage this important part of the Earth system—one that is anticipated to become ever more important to the global economy in the decades ahead.

The research community is poised for significant growth in understanding the Arctic as a system, a position afforded by recent research into the interplay of its physical, biological, chemical and social science components. The community has made great strides, taking advantage of many newly developed technical resources, including key measurements provided by Arctic observatories, advances in experimental and field-based process studies, and enhanced modeling capabilities. The Arctic is an ideal setting to design a next-generation research initiative that focuses on systems-level understanding and synthesis, which of necessity will unite a new generation of interdisciplinary scientists in fields that have traditionally remained in separate enclaves. In addition to improving our fundamental knowledge about the biogeophysics of a rapidly changing part of the world, such an initiative will mobilize the transfer of new findings into the decision-making domain. This chapter reviews the nature of the Arctic as a system, why it is important to study and the exceptional character of the Arctic as a testbed for forwarding systems-level thinking. We also present the allied notion of synthesis.

1.1. The Arctic as a System

The Arctic can be thought of as a highly interactive system (**Box 1.1**). It is an integral part of the larger Earth system, acting as a throttle on global energy balance and exerting strong influence on the climate dynamics of the more temperate regions (**Box 1.2**). It is perhaps more accurate to consider the Arctic as a complex system connected through a series of tightly linked processes that define interactions among its physical, biological and human components (NRC 2014) (**Figure 1.1**). Polar regions provide the essential heat loss at the end of a planetary-scale energy transfer system. Both poles re-emit back into space the energy gained primarily by solar insolation in the lower latitudes, after this energy has been transported long distances poleward through atmospheric and oceanic circulation processes. In so doing, the high latitudes play a critical role in maintaining stability in the Earth's energy balance.

Along with these energy fluxes are material transports. A good example is with water: reversible phase changes from ice to liquid to vapor not only trade energy but also link biological and social systems that vary greatly over the year because of asymmetries in energy balances associated with the long polar days and nights. The Arctic is also a place where huge quantities of biotic carbon are fixed via photosynthesis and released through decomposition, although these two processes are not necessarily in balance. As carbon fixation exceeded decomposition over long periods of time and with the land mass then frozen, tremendous stores of carbon were locked into Arctic permafrost. Today, these stocks can now be liberated as the climate warms, sometimes tens of thousands of years after their initial sequestration (Drake et al., 2015).

The Arctic system also holds important feedbacks and potential tipping points of planetary consequence. For example, the well-known sea ice-albedo feedback, through which the excessive melting of sea ice opens a highly absorptive liquid surface to solar heating during the summer months, greatly increases the net gain of energy by the ocean. Warming this surface water in the Arctic Ocean then makes it increasingly difficult to re-freeze the sea ice—a quintessential positive feedback expressed through the coupling of water and energy (Kashiwase et al., 2017). Additional feedbacks—of which there are many and discussed at numerous points in this report—link Arctic system physics, chemistry and biology, but have yet to be fully assessed and harbor significant unknowns (Francis et al., 2009a,b).

Recent concern regarding the state of the Arctic system and its possible trajectories into the future derives from growing evidence that it is already experiencing rapid and amplified signatures of global climate change *and* that Arctic change could itself be a critical throttle on planetary dynamics (NRC, 2013, 2014). Changes are already impacting life systems and economic prosperity, and continued change is expected to bear major implications far outside the region (ACIA, 2005; AMAP, 2012; Melillo et al., 2014; IPCC, 2007, 2013). Ongoing assessments of the sensitivity of Arctic environmental systems to change remain highly uncertain (Hinzman et al., 2013; Francis et al., 2009a). At the same time, we have entered an era when environmental management, traditionally local in scope, must confront regional, whole biome, and pan-Arctic challenges and begin to provide insight to policymakers and managers with regard to solutions.

These research challenges will test the current capacity of the Arctic research community to not only address questions that are fundamentally interdisciplinary but also multi-scale, systems-oriented and policy-supporting. Understanding the Arctic system must encompass many orders of magnitude

Box 1.1. What is a System? What is the Arctic System?

An intuitive definition of "system" is a set of interconnected components that together form a complex whole. The human body is a system, as is the internal combustion engine, the transportation network of a city, or the social and legal fabric of an indigenous community. The Arctic, much larger than any of these examples, is a system that is woven together by both its biogeophysical and social components. For the purposes of this report the Arctic system comprises, the North polar region, with the Arctic Ocean and its peripheral seas; the surrounding land mass that collects water, energy, and constituents and delivers these to the ocean; and the overlying atmosphere (**Box 1.2**). Each of these major components has dynamic interactions within the Arctic and exchanges with the broader Earth system—for example, land-to-ocean fluxes of water, energy, and constituents via rivers draining the land mass; Atlantic-Arctic Ocean water transfers at the surface and at depth; and atmospheric teleconnections with the lower latitude weather systems.

One important and common feature of systems is that the manner in which they function cannot be understood by focusing solely on the dynamics of their individual components. Attaining a systems-level understanding requires exploration into the connections that bind the subsidiary components together, as well as the emergent properties that result from their interactions. Understanding systems means that researchers must be able break them down into yet smaller subsystems in order to study how each sub-unit functions individually and ultimately interacts with other components inside the larger system. For example, part of an internal combustion engine is its electrical subsystem, which in turn is intrinsically connected to both the monitoring and operation of the engine—and, in today's vehicles—navigation and even self-driving functions.

A second common attribute of systems is that they are sensitive to the types and quantities of energy by which they are powered. For example, if someone changes their diet to eat fewer fatty foods, system components such as digestion and metabolism respond, and may likely improve the performance of the system as a whole. A third important characteristic of systems is that their functionality is compromised should one or more of their key components begin to break down. For example, if the air filter on an internal combustion engine is not replaced at the recommended mileage, then system components from the powertrain to the fuel injectors will no longer operate in concert; the engine will run poorly and could conceivably stop altogether.

In the study of systems there is also the inherent issue of scale or granularity. The Arctic system as considered in this report refers to the set of interconnected processes that may be generated at very local (or even sub-molecular) scales that ultimately produce dynamics over the pan-Arctic domain. The processes operate from milliseconds to centuries and beyond. At the same time, one does not necessarily need to understand the physical chemistry of water, such as its orbital configuration at the molecular scale, in order to understand the hydrology of permafrost over a square meter patch of landscape, over permafrost-dominated watersheds or its disappearance across the entire Boreal zone. It is important to recognize also that the Arctic system is itself a part of a global system, and how it links to the larger Earth system is essential to determining the implications of climate, environmental, and human dimension change.

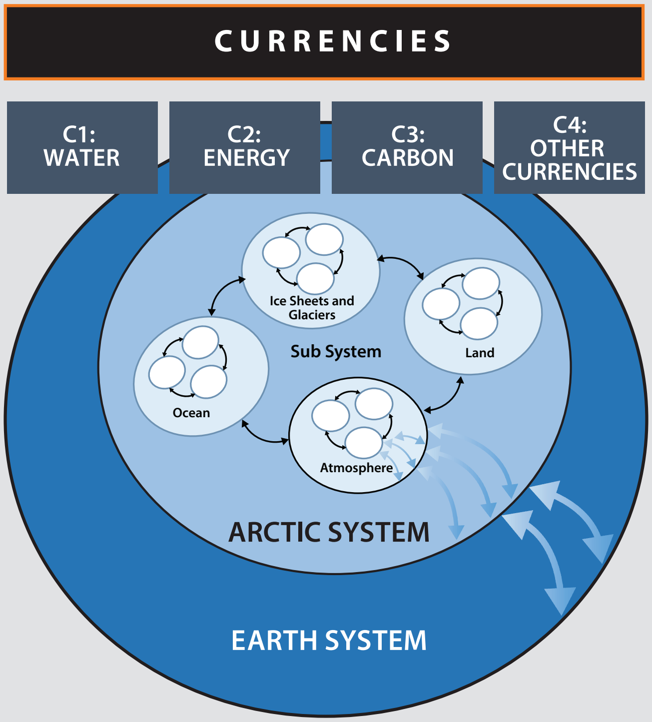
across both space and time, yet much of the current research on the Arctic is typically defined, because of practical limits, by particular sets of questions at particular scales and on individual processes, and these have not been unified under the umbrella of Arctic system science. The current culture of research, which has also been focused by tradition on individual disciplines and is curiosity-based, may be less than optimally suited to meet these new grand challenges.

Many linkages and trajectories of change between the Arctic and larger Earth system (Box 1.2) remain unclear. Among these is one that is critical to humans living outside the Arctic, namely the outsized warming of the Arctic compared to lower latitudes, and a process called *Arctic amplification* may influence the polar front jet stream and hence weather patterns well into the lower latitudes (as explained later in Box 3.4)—yet debate remains. Widespread thaw of permafrost in response to Arctic warming will lead to a significant release of carbon to the atmosphere, causing further warming throughout the global climate system, but determining the amounts and type of carbon that will be released remains an area of active inquiry (Shakhova et al., 2010; Ruppel, 2011; Drake et al., 2015; Jones et al., 2017). And, in what is the best-known of planetary-scale impacts of Arctic warming is

Box 1.2. Defining and Studying the Arctic System: Dynamics and Currencies

For this report, we define the Arctic system as a suite of coupled atmosphere, ocean, and land subsystems distributed across the high northern latitudes, interacting with themselves and the lower latitudes of the Earth system (Swanberg and Holmes, 2013). These interactions and interconnections can best be viewed as a series of *currencies*, the most important of which comprise the cycles of water, energy, carbon, and major biogeochemical nutrients (e.g., nitrogen, phosphorus). These currencies can be studied as stores (stocks), the quantities of which vary over time and are tracked via observations or simulation modeling. These currencies also embody vectors that connect them to each other over space and time, and transfer the currencies through physical, chemical, and biological means. For a complete rendering of the system, we must superimpose onto this biogeophysical definition human society and economic dynamics.

The focus of this report is on how major currency stocks and their linkages translate into broader system-level behaviors. Given the rapid and ongoing changes experienced over the pan-Arctic domain, it is not possible to study a system at steady state. Research therefore needs to be focused on the dynamic flows of mass and energy through all of the contributing subsystems as well as within the overall system itself, plus all of their changes over a range of contrasting temporal and spatial scales. While it is important to recognize the essential role of studies that explore the individual and often highly localized systems-level dynamics that ultimately define Arctic dynamics, in this report we focus on the challenge of understanding the *Arctic system* as a whole, that is, through studies of the collective behavior of interconnected currency processes that ultimately define conditions at the full, pan-Arctic scale. Of course, the Arctic is itself part of a larger global system; therefore, forcings—external factors—that are imposed on the Arctic from that larger domain, as well as the feedbacks passed back to the Earth system from the Arctic, must also be part of this research agenda.



This multifaceted Arctic system is complex, and as we will demonstrate, studying it requires an integration of many different supporting technologies and approaches. This means a rich interplay of process-based experiments; large field campaigns; process-level, pan-Arctic, and Earth system modeling; and synthesis. All will be necessary to develop predictive capabilities in a system well-known for its departure from steady-state conditions. This arena of research provides a promising testing ground for innovation in both the sciences and policy domains.

the melting of glaciers and ice sheets, contributing directly to accelerated sea-level rise (Kopp et al., 2016).

Some major system-level interactions involve direct human management. The Arctic is increasingly affected by the migration of financial capital from the south as reduced sea ice extent attracts increased shipping and marine traffic, tourism and resource extraction, and as economically important species of fish extend their range northward. As resources across the Arctic are tapped, the region will grow in economic and strategic importance, but will this occur peacefully or will conflicts arise? Just as the biogeophysical aspects of Arctic-Earth system interactions remain a challenge, so do its human domain questions.

1.2. Arctic Systems: Societal Concerns and Decision-Making

Over the last decade, national governments both in the United States and around the world have recognized the importance of the Arctic, as evidenced by several high-level planning documents and administrative declarations (Bush, 2009; Obama, 2014, 2015; IARPC, 2016; U.S. Department of State, 2017; Arctic Council, 2017) (**Box 1.3**). In the United States, strategic planning documents developed over the last decade also point to the Arctic, and indeed the Arctic system, as a key arena of national concern from scientific, diplomatic, military, and private sector perspectives. U.S. Arctic Research Commission *Goals and Objectives Reports*, which help to prioritize agency and interagency investments in Arctic research,

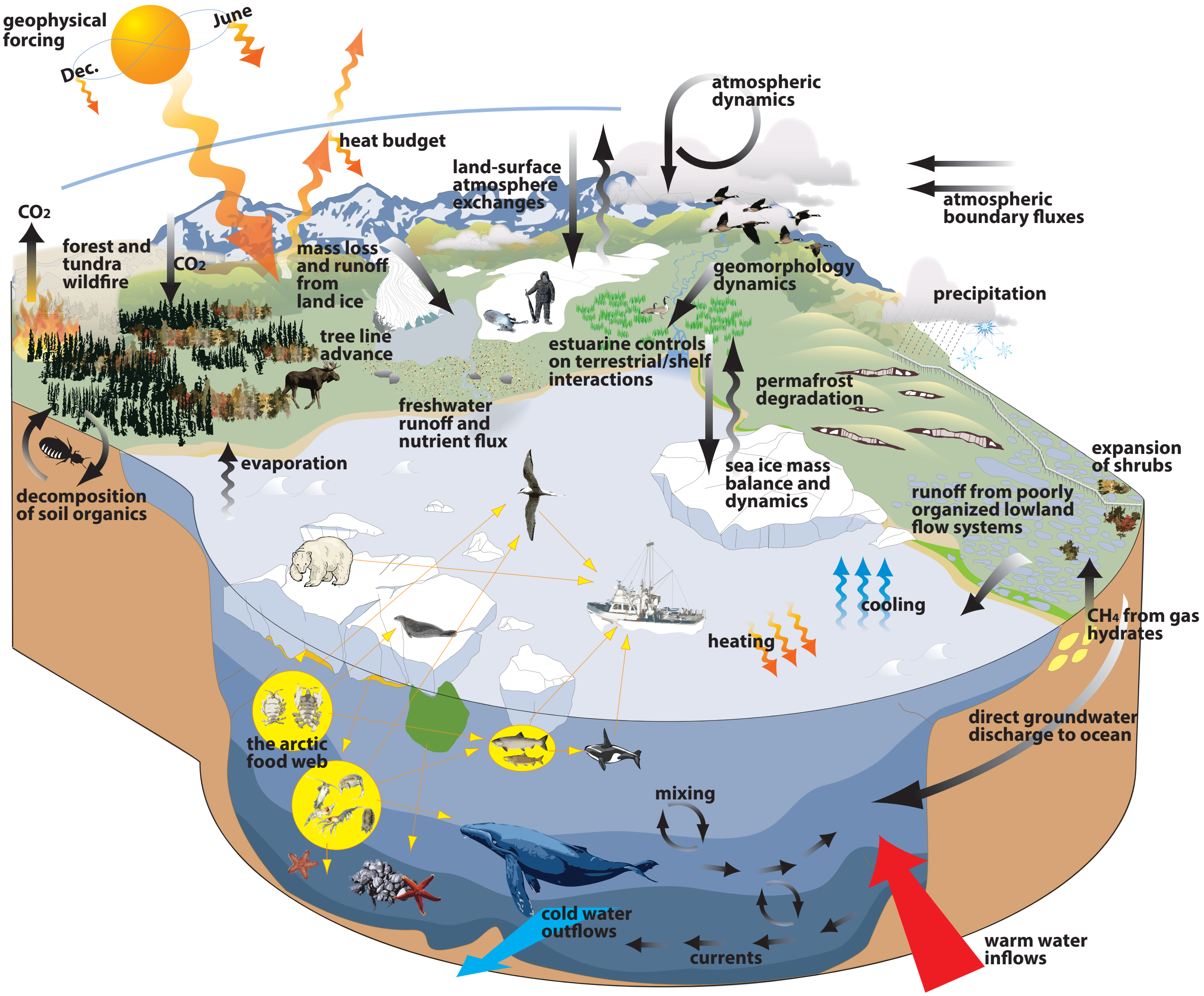


FIGURE 1.1. Component state variables and dynamic processes operating in the Arctic. There are strong couplings, feedbacks and nonlinear behaviors arising from their interactions, which together define the Arctic system science challenge. *From Roberts et al. (2010).*

have presented several systems-level challenges and research topics, one example being the paradox of increasing precipitation with simultaneous drying across the Arctic landmass (USARC, 2016), which requires analysis of interactions linking the climate system, ecology and biogeophysics. A capstone of accelerating U.S. and international interest in the Arctic was recently reflected during the U.S. Chairmanship of the Arctic Council (2015–2017) and its four themes, which were all arguably systems-level: Arctic Ocean safety, security, and stewardship; building Arctic community resilience; recognizing and responding to climate change; and raising Arctic awareness as a fundamental part of the Earth's natural systems and economy. Additional challenges and commitments were described in the recent *Fairbanks Declaration* (U.S. Department of State, 2017).

Systems-level understanding is also essential to articulate the Arctic's role in the global economy. Yet, this societal impact question cannot be addressed in a vacuum and needs to identify the economy's key interactions with the Earth system. Such understanding is an important foundation that defines the playing field of the future—the rapidly shifting environment in which the Arctic economy will need to operate. The Arctic's climate resiliency and long-term sustainability will depend on policy decisions made today that will drive its economic development, sustainably or not. While fundamental research is essential, if left unguided by the needs of policymakers it may fail to provide critical knowledge for decision-making in an era of change. A broader science agenda, co-generated through a partnership among scientists, policymakers and stakeholders, will arguably be necessary in

Box 1.3. Examples of Societally Motivated Demands for Knowledge About a Changing Arctic System

Because of rapid, if not unprecedented, rates of change, the Arctic is today home to a suite of trillion-dollar concerns—both positive and negative—on the global economy. Examples are as varied as global trade and the opening of new trans-Arctic shipping routes, increased or impeded access to land and ocean-based resources, degrading ecosystems, the opening of new fisheries, upheaval in subsistence resources, damage to infrastructure on fragile coastlines and the constructed environment, Arctic sovereignty and national security concerns, and climate adaptation and mitigation. While these many issues may appear to operate in isolation, they emerge very much within the context of an evolving, integrated Arctic system defined by many interactions among its major natural and social subsystems. Biogeophysical dynamics must be understood in terms of their coupling to social systems, yet this aspiration crosses traditionally entrenched disciplinary boundaries. Nevertheless, such a perspective is a necessary precursor to forecasts of the implications of policy decisions made today on the Arctic system of tomorrow, realizing that there could be decade-to-century legacy effects of any decision made today.


Credit: L. Whitaker


Credit: Bee Wuethrich, from http://forces.si.edu/soils/04_00_31.html


Credit: John Cloud, NOAA


iSockphoto

order to ensure that we develop the tools and understanding to address evolving societal concerns.

The well-documented sensitivity of the Arctic environment and the potential long-term legacies or irreversibilities generated by today's—or any future—strategic management decisions will play themselves out across the region's natural, physical, social, and economic subsystems. This makes systems-level understanding essential for identifying feedbacks and tipping points. Relevant examples include the management of wildlife populations through hunting regulations and the consequent impacts on plant biomass (Russell and Gunn 2012; Joly and Klein 2016), with plausible additional impacts on permafrost or even microbial dynamics that feed back to the emission of radiatively important gases like methane. Other examples include the long-term impact of wood harvesting in boreal forests (Krawchuk and Cumming, 2011) or black carbon management (Sand et al., 2013). Projecting the stability, or alternatively the vulnerability, of ecosystems and coastlines, which is still today a fundamental systems-level challenge, is a key information demand voiced by community planners as they develop plans related to potential relocation (Vörösmarty and Hinzman, 2016). The capacity to analyze such a "decision-impact-next decision" space has yet to be developed and would represent an excellent partnership of knowledge providers and consumers.

Some Specific Societal Impact Areas

Transport and Shipping. Over the last two decades, there has been a dramatic increase in Arctic marine traffic, including shipping, supply, research, tourism, and search and rescue. Traverses of the Arctic as documented by the Automatic Identification System (AIS) have proliferated. (Figure 1.2). The increase in navigability and interest in the Arctic region is accompanied by a rise in telecommunications capabilities, both via undersea cables (e.g., the Quintillion project in Alaska) and satellites (e.g., Iridium). Such development requires a degree of certainty with respect to business and infrastructure operations (reducing surprises, thresholds, and unintended consequences). The Arctic Investment Protocol Guidelines for Responsible Investment in the Arctic (WEF, 2015), adopted by a growing number of those engaged in Arctic development, lays out six principles that are possible to achieve only through deep knowledge of the Arctic as a system.

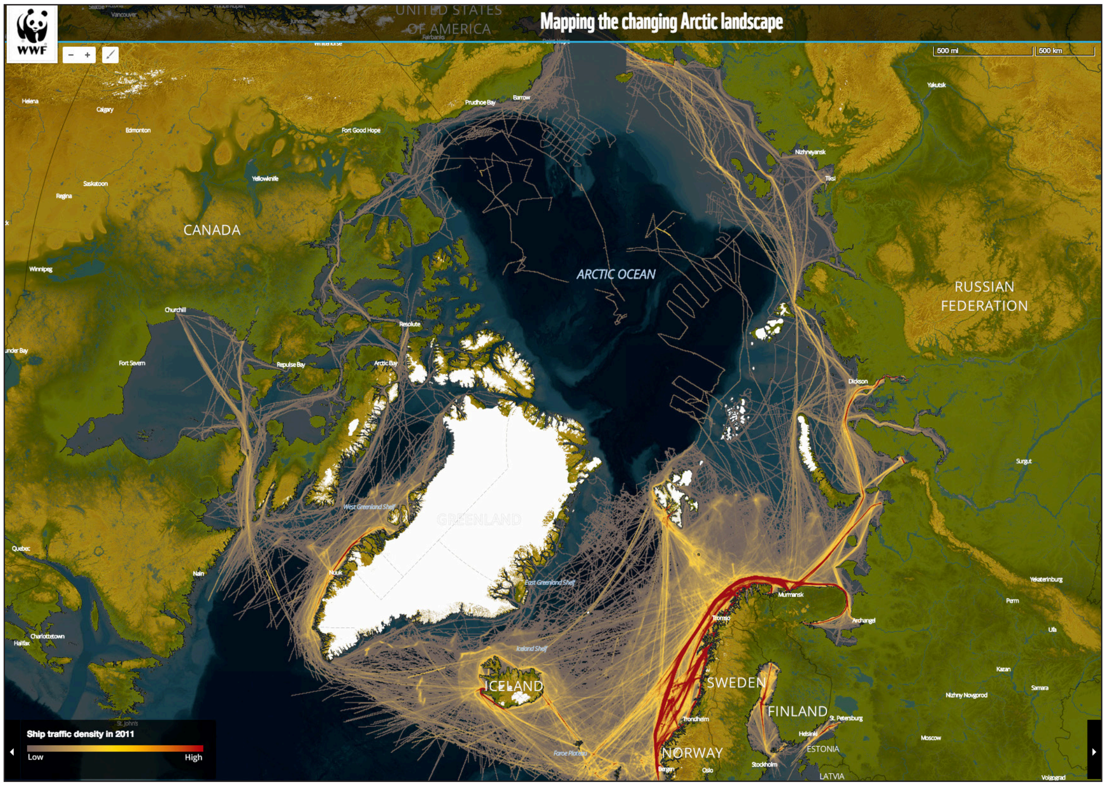


FIGURE 1.2. Arctic shipping traffic density for 2011. Much of the ice-free Arctic ocean today hosts ship traverses for cargo transport, ocean exploration, and passenger and tourist traffic. While the traverses show the result of lower latitude economic forces moving northward, the image also shows the Greenland Ice Sheet, a looming Arctic source of sea level rise that will create substantial threats on those same lower latitudes and indeed throughout the globe. Source: http://wwfarcticmaps.org/.

Energy and Mineral Extraction. The Arctic has emerged as a global focal point for energy development with 5.9% of the world's known oil reserves and 24.3% of known natural gas reserves (AEC, 2016). If the Arctic were to be considered a country, it would rank at the top of lists assessing resource potential. The Arctic also holds enormous potential in minerals, much of it contained within the Arctic Ocean seabed. Access to these resources has increased with sea ice loss, although milder winters have sometimes made access to terrestrial oil and gas through ice roads more problematic (Levin, 2017; Wang, 2017). The current state and future trajectories of heat dynamics over land (e.g., disappearance of permafrost) and sea (e.g., ice navigation challenges) require forecast capabilities, which in turn require fundamental systems-level understanding.

Arctic Change, Society and Economic Development. Arctic system dynamics are critical to understand in order to address the needs of Arctic residents, including unique Indigenous societies, in the context of rapid change. Figure 1.3 illustrates how a series of closely linked processes defines a precarious balance between the Arctic environment, food sources, Indigenous livelihoods and, hence, their culture. The diagram is a systems-level depiction of the key elements and their interconnections, with an enormous degree of coherency between this Indigenous people's view of the Arctic system and that of modern researchers (Figure 1.1, Box 1.2). Understanding the changing Arctic system, therefore, is of critical interest to Arctic Indigenous communities, which need to be consulted early and often in order to co-design a research agenda that is relevant to their sustainable development (ARCUS, 2018a). Traditional and Indigenous knowledge should be incorporated (e.g., the Sea Ice for Walrus Outlook; ARCUS, 2018b), and efforts should be made to effectively communicate the results of Arctic system research so that it can be used by all relevant stakeholders.

Wildlife and Wildlife Management. Wildlife across the Arctic is an intrinsic part of the system and keenly tuned to the character and trajectory of the environment. A case in point is for muskox and climate-related disease. For these animals (and also for caribou and reindeer), shifts in the seasonality of precipitation, and the rise in number and severity of rain-on-snow events have negative impacts. These events typically do not cause problems when they occur in the spring, but they can decimate reindeer populations if they occur in the autumn

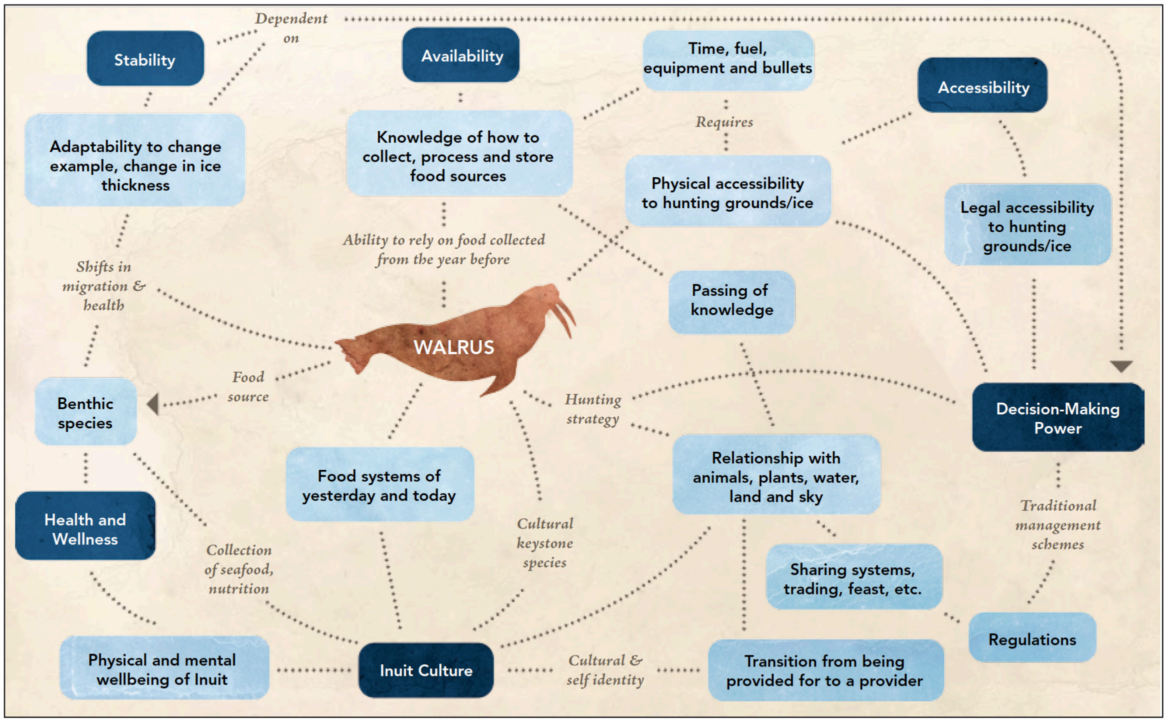


FIGURE 1.3. Conceptual model of the Arctic system, depicting linkages of consequence to Alaskan Inuit food security from an Indigenous people's perspective. While the technology, culture, and languages of the Inuit are radically different from the scientists engaged in the Arctic science research community, the depictions of the system are strikingly similar. From Inuit Circumpolar Council-Alaska (2015); reprinted with permission.

when a thick ice crust can form, hampering scavenging fodder under the snow. Such events occurred in 2006 and 2013, causing mass starvation of reindeer herds in the Autonomous Okrug of West Siberia, and scientists have traced this biological system collapse to extreme weather in the coastal mainland in northwest Russia, together with sea ice loss in the adjoining Barents and Kara seas (Forbes et al., 2016). These extremes, in turn, have interacted with biological systems (i.e., vegetation state, nutrition, climate-associated diseases), subsistence, sport and commercial harvesting, a clothing industry and the social and economic fabric of local inhabitants.

1.3. Defining Arctic System Synthesis

As befitting a report on synthesis science, a short discussion on what is meant by *synthesis* is in order. This report uses a simple, pragmatic and operational definition: *A coordination of thought to elucidate system function and emergent system properties.*

While the concept of synthesis might be viewed as well-established, there is actually substantial disagreement on defining its salient aspects and how best to execute associated analyses; this debate has involved the likes of Newton, Riemann, Liebnitz, and Gauss (Ritchey, 1991). Typical definitions offer the simple idea of a "whole" from its "parts." Yet a pathway toward this "whole" can be taken via an inductive route (taking observations of specific conditions and integrating them into a picture of the general whole) or through deductive logic (applying general principles to predict, often through modeling, specific outcomes).

Thus, synthesis is the process of combining diverse research perspectives using both inductive (observation-based) and deductive (model-based) approaches executed by collaborative teams to uncover system-level behaviors not otherwise predictable by study of the individual parts. The Arctic system makes possible this interplay between inductive and deductive pathways because of recent, rapid advancements in both the observational underpinnings and simulation capabilities depicting the Arctic system and its principle sub-components (**Box 1.4**). These two main lines of attack with respect to systems-level analysis will be at the heart of understanding the contemporary and future Arctic.

1.4. Two Systems-Level Research Challenges

It is not difficult to list many important Arctic processes that occur at a variety of spatial scales (USARC, 2010) and that legitimately fall within the rubric of Arctic systems analysis. Two themes, among many others, have been analyzed as part of this planning process. Neither attempts to be comprehensive but, instead, emblematic of the type of scientific questions and issues that could be addressed by integrated, systems-level study. These two themes are essential research challenges, and both have to do with currencies. The first is about defining the behavior of currencies within a coupled Arctic system—their basic distributions over space and time, their interconnections, and how they combine to produce holistic behaviors. The second relates to how the currencies participate in climatically induced extreme events both as potential causal agents and as impacts of such events.

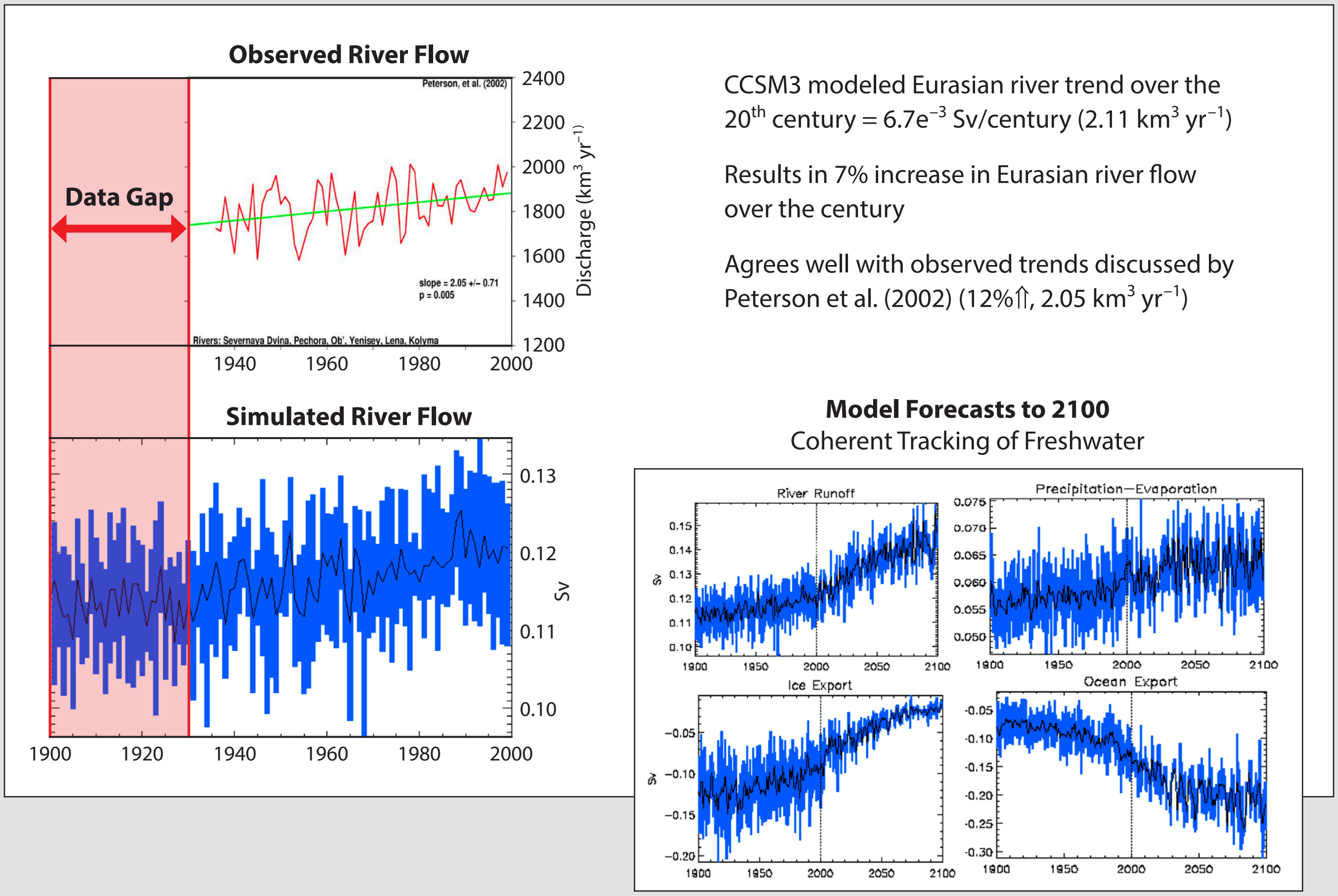
Systems Research Challenge 1: Currencies as a Critical Component of the Arctic System

As introduced briefly in **Box 1.2**, this report defines a "currency" as a geophysical entity that possesses quantifiable properties. The state and dynamics of the Arctic system can conveniently be organized as the study of the currencies for energy, water, carbon and other biogeochemical constituents. As within a bank account, currency can be stored for future use, as a *stock*, or withdrawn, as a currency, in *flux*. For example, the seasonal accumulation of snow represents a stored stock of water as the currency, which is later transformed into a flux during the annual spring freshet that transports continental runoff through rivers that ultimately finds its way to the ocean.

One currency can affect the distribution of another. For example, rivers transport energy, carbon and nutrients from land to sea. Carbon preserved in permafrost is a frozen asset until the ground thaws; i.e. a phase-change of water turns the fluxes of carbon and water on and off across seasonal and millennial timescales. As another example, Arctic system currencies of energy and water are necessary in order to create a storage of carbon in the form of a plant, with all three currencies contributing to the fluxes at the leaf surface that define the capacity of the plant to fix carbon. These dynamics start with an inherent time domain associated with the photosynthetic process, with responses that take place over the span of seconds up to diurnal cycles, seasons, multiple years, decades or hundreds if not thousands of years, and as plant remains become incorporated into soils and permafrost. Moreover, the spatial distribution of plants, along with their climatic and biogeochemical drivers, define the regional or pan-Arctic accumulation of fixed carbon, integrating the land surface energy, water and nutrient balances over these many time horizons. Arctic system researchers therefore confront an important challenge—how to keep track of a system that is capable of storing and transferring water, carbon and energy across domains spanning a single leaf surface, a watershed or the entire Pan-Arctic.

Box 1.4. An Example of Combining the Two Major Avenues Toward Synthesis (Induction and Deduction) in an Arctic System Context

A custom-made example of this approach emerged from the Freshwater Integration Study of the NSF-ARCSS funded Freshwater Integration Study (Holland et al., 2007). From earlier work (Peterson et al., 2002), a multidecade, secular trend in increased runoff was noted in the large Eurasian rivers flowing into the Arctic Ocean, setting up a major challenge to the community to identify causality and explain the ramifications of this trend. Several potential sources (from thawing permafrost to increases in precipitation) were identified and most discounted either due to the paucity of data or infeasibility (McClelland et al., 2004). For example, sustained increases in river discharge invoke the expectation of accelerated levels of permafrost thaw, which indeed have not been observed. An earth system model—with, at the time, improved characterizations of the Arctic atmospheric, ocean and land-based arms of the hydrologic cycle—was put to the task of explaining the trend. The simulation was able to track the coordinated response of the system to increased heating together with poleward fluxes of energy and water entering into the Arctic region. Remarkably, this net input of precipitation over evaporation (referred to by climate scientists as "P minus E") could explain both the historical trajectory and magnitude of the increase in flux, equivalent to the observed trajectory of river discharge, at least on annual timescales. The coupled nature of the dynamics also demonstrated a net decrease in ice transport out of the Arctic Ocean with a simultaneous net increase of liquid freshwater flux.



CCSM3 modeled Eurasian river trend over the 20th century = 6.7e^{-3} Sv/century (2.11 km^3 yr^{-1})

Results in 7% increase in Eurasian river flow over the century

Agrees well with observed trends discussed by Peterson et al. (2002) (12%⇑, 2.05 km^3 yr^{-1})

Model Forecasts to 2100
Coherent Tracking of Freshwater

In this continuum, a particularly critical phenomenon that characterizes the Arctic and directly impacts currencies is its strong seasonality as it moves between frozen and unfrozen states. Phase change can revert a currency from a stock to a flux, as when ice melts and runs off a hillside or as organic carbon is decomposed and released as CO_2. The processes can be exothermic—as when latent heat energy is released as liquid water is converted to ice—or endothermic, when latent heat energy inputs are required to convert liquid water to vapor. Energy input is also required when gaseous CO_2 is converted to solid organic matter through the endothermic reaction called photosynthesis. A reciprocal exothermic reaction occurs when energy is released as organic matter decomposes, transforming carbon in solid phase into gaseous CO_2 or methane. These processes demonstrate how a complex system is configured through this patchwork of linked processes.

Systems Research Challenge 2: Extreme Events in the Framework of Currencies

The second major topic emphasized in this report is on extreme events—their genesis, evolution and ultimate impact on both the Arctic and larger Earth system. Issues of positive (or negative) feedbacks, tipping points, and the affiliated notion of resilience or lack thereof, are part of the dialogue. These have clear societal implications with very real impacts on Indigenous lives and livelihoods. Considering the amount of current and anticipated future investment in a broad spectrum of modern economic activities, there are potentially huge losses and great uncertainty as continued environmental and climate change will place these activities and the critical infrastructure they depend on at the forefront of risk.

In climate science, an extreme event is viewed as a statistical outlier, such as a precipitation or temperature event in the top 1% of a given statistical distribution. The timescale of such events might range from daily to seasonal, or even longer. A purely statistical definition may not be appropriate for other types of extremes. For example, a massive die-off of reindeer or caribou could certainly be considered an extreme event, as would an oil spill having major ecological effects. However, a common thread is that extreme events, however defined, are akin to hitting the Arctic system with a hammer. When part of the system is hit hard, impacts may reverberate through other parts of the system. By looking at these reverberations, we can understand more about the system as a whole, including the connectivity of the components and their individual resiliency.

Extreme events typically involve large exchanges of currencies of energy, water and carbon. For example, while a winter with extremely high precipitation over the terrestrial Arctic could be understood in terms of the transport of unusually warm and moist air (i.e., energy and water currencies) from lower latitudes, reverberations of this event may include extremely high river runoff and transport of dissolved carbon or nutrients to the Arctic Ocean. These effects, in turn, influence phytoplankton blooms, microbial decomposition, and, through the influence of freshwater inputs on ocean stratification, nutrient concentrations and sea ice formation well into the following autumn. Hence, the initial event and its ultimate repercussions link the atmosphere, land, ocean and biology together within an Arctic system. Another category of extreme event would be a massive oil spill, precipitated by the failure of a single piece of equipment. However, the impacts of this event are likely to cascade through many human and biological pathways, and necessitate a systematic approach to quantifying the effect of one sub-system component upon another. This is needed before a full-system understanding of this kind of extreme event—and a proper risk-management strategy—can be secured.

1.5. Building Capacity for Arctic Systems Research

The last 10 to 15 years have been a period of remarkable scientific development, enabling several new dimensions of Arctic research to develop. This includes: advances in genomics; big data and data assimilation; remote (including microsatellite), autonomous and in situ sensing; advanced field experiments, cloud computing, GIS data sets and their analysis (**Figure 1.5**).

The Arctic can serve as a quintessential testbed for systems-level synthesis and modeling. While the community is poised for advancement, progress has been hampered. Some of this owes to the traditions of individual disciplines, with differing approaches, nomenclatures, time and space scales (USARC, 2010). But there has been no dedicated or sustained program to mobilize the community, integrate the tools and organize scenarios and experiments around the new emerging capabilities. New opportunities today present themselves as NSF has recently laid out an ambitious research agenda in its 10 Big Ideas, which can straight-forwardly be linked to Arctic system science and synthesis (**Box 1.5**).

The remainder of this document describes a community view on how to shape programs like NSF-ARCSS and other agency initiatives to achieve this goal. We first review the scope of the science such programs would have to confront, reviewing the issues in light of currencies and environmental extremes. There are five goals for this report, each designed to advance thinking about a next generation of Arctic system science. The goals:

- Summarize recent progress in Arctic system synthesis, identify remaining challenges, and present new opportunities in this emerging field as they relate to basic research, applied research, and the generation of policy-informing knowledge;
- Explore in more depth the concept of currencies, using energy, water, carbon and biogeochemical constituents as a vehicle to enable improved quantitative understanding of the connectivity among system elements;
- Consider extreme events in the framework of currencies to characterize the connectivity of components within and the resilience of the Arctic system;
- Use currencies as an organizing framework to help inform policy and improve decision-making; and
- Review and assess the necessary institutional support for meeting the challenges and opportunities, and reflect on potential new modes of executing synthesis that would be appropriate to the Arctic and its community of researchers, policymakers, and practitioners.

The remainder of this report is structured to support these goals. It starts with a rationale for studying the Arctic as a system, and indeed how its biogeophysical and social properties make it an ideal candidate for advanced systems analysis. Next come the two worked examples, depicting currencies and then extremes. For each topic, there is a definition of our current level of understanding in a systems-level context. Then follows a section on approaches and tools for executing synthesis. This includes discussion of observatories and monitoring networks, remote and in situ sensing systems, data assimilation and other analytical approaches, and modeling. To broaden the value of this assessment, the report demonstrates how Arctic synthesis studies can better inform policy and environmental management. The formal narrative concludes with some of the needs and characteristics of a synthesis support program for the Arctic system science research community, sponsored by one or more of the IARPC agencies. Additional information is provided in four appendices, listing: the organizing and drafting committee personnel; workshop participants; references and additional background readings; and, acronyms and abbreviations.

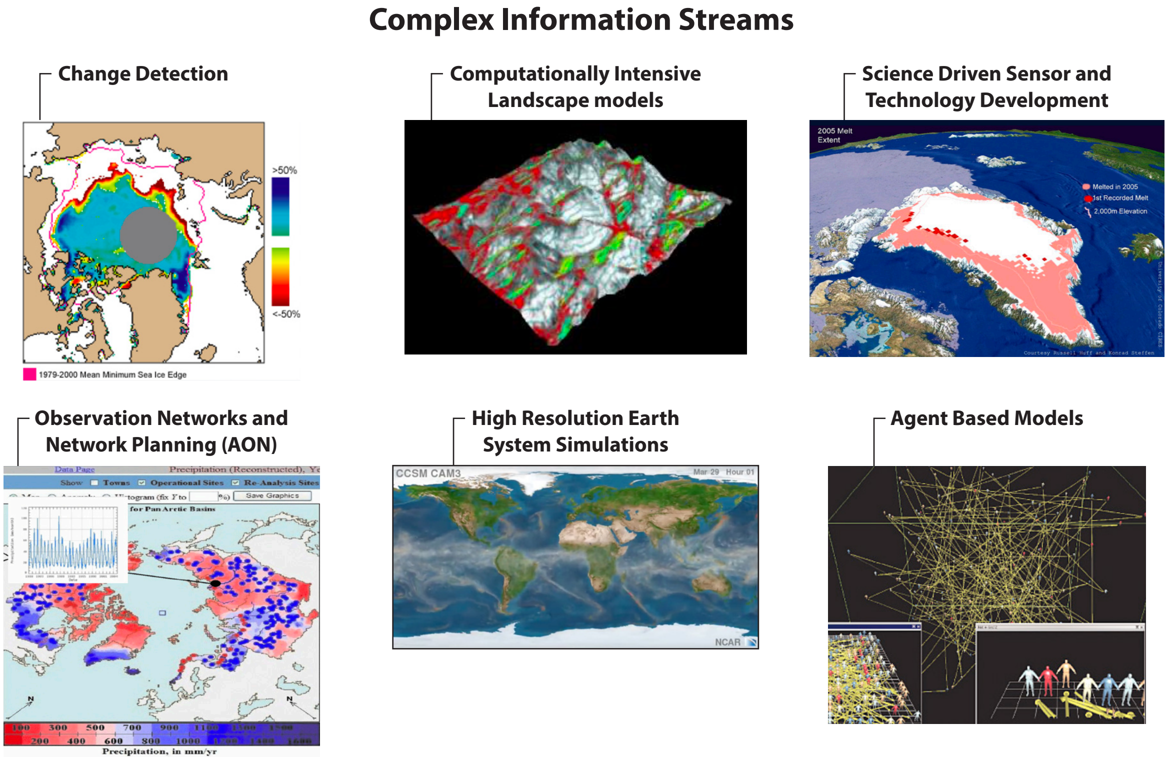


Figure 1.5. Complex information streams are increasingly able to characterize the Arctic system's state and state of change. Recent research has begun to uncover the processes at work at scales from local to pan-Arctic. Correspondingly complex data sets have also emerged in tandem. Recognizing and then integrating across process-level understanding and reconciling hypothesized or simulated linkages to the observational record is at the heart of systems-level understanding and synthesis.

Box 1.5. Arctic Systems and NSF's 10 Big Ideas

In 2016, the National Science Foundation presented its 10 Big Ideas, 10 major, transformative research themes that will guide its agenda for the next many years. These challenge areas span the breadth of the Foundation, encompassing the worlds of cybertechnology, human-technology synergy, and quantum revolution. Among the 10 ideas is the notion of Convergence, a concept which took root in the early 2000s (NSF/DOC, 2002) and that itself unites several arenas of more traditional study—the geosciences, engineering, and computing and informatics, and social, behavioral, and economic research. Convergence Research is intrinsically transdisciplinary—which the Foundation has forwarded as a major organizing concept for many of its research investments over the last two decades—but it goes well beyond this.

Convergence in scientific research is a process that can be defined as the consolidation of advancements in different arenas that are brought together to produce knowledge or to solve a problem that is bigger than any single discipline could possibly address. Convergence Research takes advantage of leading-edge ideas, methods, and technologies that may by themselves be pivotal to progress in a particular area, but when assembled within a new transdisciplinary problem domain, greatly accelerate progress. A good example is how Convergence thinking can unite Earth system science, industrial ecology, engineering infrastructure, energy system analysis, economics, and social system dynamics to help design a more sustainable twenty-first century (Diallo et al., 2005). Other examples of Convergence Research span many fields and include the medical sciences, national security, improved institutional governance, and unifying science and education (NRC, 2010; MIT, 2011; Roco et al., 2013).

Thus, Convergence in the research domain is characterized by multiscale, transdisciplinary, and of necessity, team-based research. NSF has framed Convergence Research to encompass two interacting characteristics. The first it calls *deep integration across disciplines*, wherein disciplinary experts join forces to attack a major research challenge that first requires identification and then consolidation of all relevant individual disciplinary theories, data sets, methods, research cultures, and nomenclature. This synergy produces breakthroughs that are fundamentally synthetic in nature. The second characteristic of Convergence is that of *research organized around a specific and compelling problem*, of either a basic or applied nature, to create a clear set of goals and coherence of purpose in pursuing them.

While posed as one of the 10 Big Ideas, Convergence in some sense also serves as the overarching theme that encompasses several of the other ideas (NSF, 2018). Among these is Navigating the New Arctic (NNA), which itself poses several transdisciplinary science challenges to which a Convergence approach will be essential. The main thrusts of this new Arctic research paradigm are fourfold: (1) they forward innovative observational platforms and networks; (2) they advance understanding and forecast capability through process studies, putting to work new insights into the principles by which living systems are organized; (3) they use advanced cyber-enabled observatory networks; and, (4) they unify engineering and biogeophysical perspectives on how best to manage risks to civil infrastructure. In this context, these NSF Convergence thrusts are constructed in order to better understand the Arctic and to then assess and enable improved adaptation and resilience to Arctic biogeophysical and socioeconomic change. The effort also recognizes the inputs and needs of the region's stakeholders, including Indigenous communities.

As will be explored through the many examples used in this report, Arctic systems research is quintessential Convergence Research. It achieves this distinction through an absolute requirement to embrace the many multidimensional perspectives by which it must be analyzed. One could, for example, view the Arctic system as a suite of interacting components and subcomponents encompassing the Arctic atmosphere, landmass, coastal zone, and ocean. At the same time, these components transcend physical, chemical, biological, and social systems perspectives. Processes link currencies and their dynamics are intertwined (**Box 1.2**). Many of the scientific community's insights regarding the Arctic have emerged from observations collected from experiments spanning scales from the bench, to the field plot, to whole watersheds, or from monitoring networks and remote sensing that span the entire continental landmass. Data assimilation models as well as advanced simulations depicting a growing variety of processes are becoming part of increasingly sophisticated Earth system models that are ever more realistically treating the Arctic. These and other approaches are highlighted in Chapter 4 of this report, and very much reflect a Convergence perspective.

CHAPTER 2. CURRENCIES

Unifying the Arctic System

This chapter reviews the use of currencies as a means to stimulate interdisciplinary and systems-oriented research. Because they can be quantified, adhere to mass and energy balance laws and are embedded deeply within the changing character of the Arctic, currencies provide a useful organizing framework, and thus are essential to any system-level understanding, at least from the biogeophysical perspective. A consideration of this assertion and five others that emerged from deliberations during the community workshops follows. While this review is not meant to be exhaustive, it does highlight some of the important roles that currencies can take in an Arctic systems context.

As described in **Chapter 1**, one of the workshop themes was *currencies*, specifically matter and energy residing within the Arctic and cycling through it, and adhering to conservation principles (**Box 1.2 and Section 1.4**). Energy, carbon, water, and the macronutrients of nitrogen, phosphorous and potassium exert the strongest controls on primary productivity on land and ocean. Individually, these have been the principal foci of simulation and observational studies (e.g., ARCSS-FWI study on freshwater, SHEBA for surface heat budgets of the Arctic Ocean). Their interactions are also critical in controlling key functions in the Arctic operating as a system. For example, the hydrologic cycle is linked to energy cycling through phase changes, to the carbon (C) cycle through controls on CO_2 and methane exchanges in ecosystems, and to the nitrogen (N) cycle through controls on its transport and availability for plants and microbes.

This chapter begins by discussing the unique role that currencies play in unifying the Arctic system. It then discusses some of the characteristic ways in which currencies operate within the system, highlighting the uniqueness of currency behaviors in the Arctic, how currencies become activated and inactivated, their legacy effects, how they amplify or dampen processes, and their interactions with geomorphological controls. The chapter concludes with a discussion of currencies in the applied domain.

2.1. Currencies: An Ideal Vehicle to Recognize the Arctic as a Highly Connected System

The individual currencies of energy, water, carbon, and other nutrients in the Arctic system (**Boxes 2.2–2.4**) provide a convenient mechanism through which to uncover and explore connections operating within the system. While analysis of the individual currencies across the Arctic can yield valuable insights (e.g., as with freshwater [Vörösmarty et al., 2001, 2002]), it is in the arena of *currency interactions* that additional insights into the functioning of the system as a whole reside (**Box 2.5**). Thus, changes in the state of one currency, by way of fluxes between the land, atmosphere, and ocean domains, affect those in another. For example, the currency cycles interact to define energy and nutrient limitations (through tissue stoichiometry), which ultimately feeds back onto photosynthesis and organic matter decomposition (McGuire et al., 1997). This close coupling means that a fluctuation or disturbance in one component will reverberate strongly into others (Hayes et al., 2011; Schuur et al., 2008; Saito et al., 2013; Francis et al., 2009b). As another example, energy produced via melting sea ice can in turn impact land-based permafrost or the polar jet stream. Despite several decades of research, major questions remain (e.g., **Box 2.1**) regarding the magnitude if not the presence or direction of linkages and feedbacks across the full system (Francis et al., 2009a).

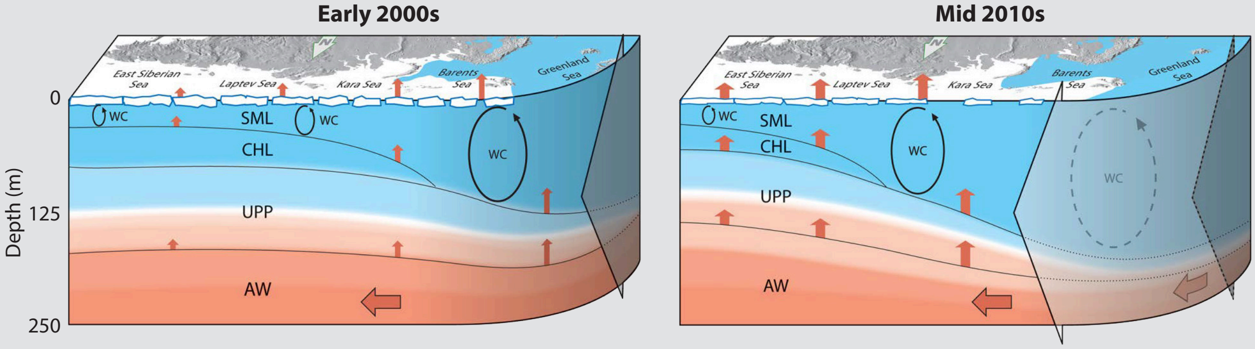
One prime example of these interactions that play themselves out in a systems context is the changes in freshwater exports through rivers, seasonally and multi-year, that influence the translocation of carbon and other river-borne constituents from the continental landmass to the ocean. Rivers also carry heat into coastal margins, and one recent study demonstrated how the Mackenzie River is a highly effective conveyor of land-derived energy into the Beaufort Sea, and ultimately contributing to the overall heat budget of melting sea ice (Ngiem et al., 2014). Once in the oceanic domain, a coupling between water and energy can also be documented with respect to sea ice, which helps to regulate energy exchanges between the

Box 2.1. An Example of a Systems-Level Currencies Challenge: Understanding the Atlantification of the Arctic Ocean and Freshwater Export

A fundamental Arctic systems research challenge relates to how climate change affects oceanic exchanges between the Arctic Ocean and lower latitudes (**Box 1.2**). The North Atlantic is where deep water forms that then feeds the Atlantic Meridional Overturning Circulation (AMOC). The Arctic Ocean affects deep water production through controls on the volume and flow pathways that control how freshwater is exported into the North Atlantic Ocean through Fram Strait and the Canadian Arctic Archipelago. At present, the North Atlantic's deep water formation sites are delicately structured in their capacity to sustain deep convection, and variations in the strength of the AMOC have far-reaching effects on global winds, temperatures, and precipitation patterns (Alley, 2007; Srokosz et al., 2012). It appears that past changes in the strength of the AMOC have occurred on decadal (abrupt) and centennial to millennial (slower) timescales. Massive increases in freshwater export from ice sheet meltwater in the Arctic, such as those that occurred during the Younger-Dryas event ~12,000 years ago, are believed to have caused a shutdown of the AMOC and a major reorganization of Earth's climate (Broecker et al., 1989).

Constraints on Arctic freshwater production and its influence on the AMOC are still not well known. River runoff feeds a large amount of freshwater into the surface layers of the Arctic Ocean, most of which is exported southward through Fram Strait and the Canadian Arctic Archipelago. Increasingly, freshwater discharge from melting of the Greenland Ice Sheet will play a role, and may already be contributing to a long-lived area of relatively cool ocean surface temperatures in the North Atlantic (Rahmstorf et al., 2015). Understanding the controls on the outflow of freshwater, and hence improving its predictability, is essential because of its influence on the stratification of the water column in the Greenland, Icelandic, Norwegian, and Labrador Seas, which serve as important regions of deep water formation (Aagaard and Carmack, 1989; Jahn et al., 2010).

The current generation of coupled global climate models predict a slowing, but not an abrupt shutdown, of the AMOC through the twenty-first century (IPCC, 2007; Caesar et al., 2018; Thornalley et al., 2018). Yet, these projections are highly uncertain (Praetorius, 2018). There are large differences among models in their ability to capture interannual variability in the liquid freshwater export. Opposing the stronger stratification owing to fresher surface waters are increased inflow rates of relatively warm Atlantic Water into the Arctic. This reservoir of heat may be shifting the Arctic Ocean's structure to one more similar to that of the Atlantic. This so-called "Atlantification" is contributing to rapid sea ice loss, especially in the Barents Sea and Eurasian Basin (Polyakov et al., 2017). In ever larger expanses of ice-free Arctic Ocean, winds may more easily mix this warm Atlantic water up to the surface, leading to further ice loss. Such changes may, in turn, affect North Atlantic marine communities and biological production. For example, Greene and Pershing (2007) show that an increase in low-salinity, Arctic-derived shelf waters into the Gulf of Maine and Georges Bank in the mid-1990s led to a major decadal-scale shift in zooplankton communities, which ultimately impacted commercially important cod and haddock fisheries that have already been overfished. These multidimensional phenomena highlight the complex processes that interact to define an Arctic system and should amply demonstrate the necessity of systems-focused research.



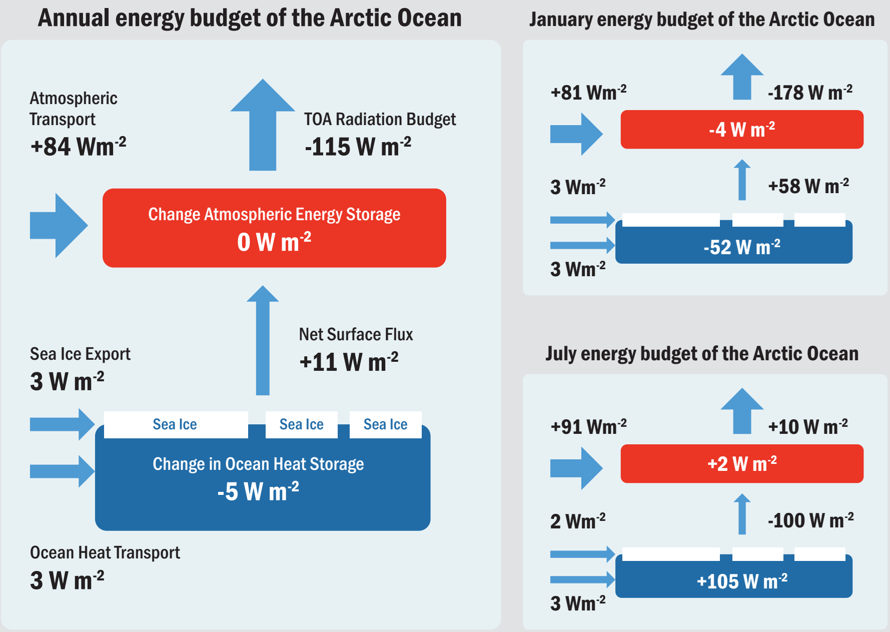
Conceptual model of "Atlantification" of the eastern Eurasian Basin continental margin in recent years. The broad arrow extending from the right side shows the encroachment of a suite of processes associated with "Atlantification": (1) increased penetration of surface signature of Atlantic Water (AW) (increased flow, heat content, or both) into the eastern Eurasian Basin (EB), (2) reduction in ice cover resulting in (3) greater surface heat and moisture flux, and (4) increased depth of winter penetrative convection, bringing additional heat and nutrients from AW into the Arctic surface water and transformation of the permanent cold halocline layer (CHL) to a seasonal halocline. SML and UPP indicate the surface mixed layer and upper permanent pycnocline. WC shows winter convection; red arrows indicate upward heat fluxes. Horizontal red arrows show inflows. From Polyakov et al. (2017); reprinted with permission, AAAS.

ocean and atmosphere and serves as an important sentinel of changes in the climate system. Ice loss amplifies warming by changing the surface reflectivity to incoming solar radiation (albedo). This sea ice-albedo feedback then leads to further impacts on atmospheric circulation and weather, as when summers with low ice extent result in higher heat and moisture fluxes to the atmosphere (Francis et al., 2009a).

Quantifying the role of changes in sea ice with respect to the Arctic's positive energy imbalance, and the impact of sea ice variability and ice-albedo feedback on Arctic energy budget, remain important research challenges, despite the well-recognized existence of these phenomena. The accumulated impact of these many intertwined processes also affects the general circulation of the atmosphere (Ramanathan et al., 1992), which for the Arctic translates into intensified warming toward the poles, or the co-called "polar amplification" effect (Figure 2.1).

The Arctic landmass is also rich in such cross-linkages. For example, hydrologic processes operating within river basins are tightly coupled to energy, carbon and biogeochemical currencies. Local permafrost conditions and interactions with water ultimately determine the rate of permafrost thaw as well as soil carbon decomposition. The spatial and temporal dynamics of surface and subsurface water across Arctic landscapes exert a fundamental control on the surface energy balance and thermal regimes inside the ground and thus the vulnerability of permafrost to climate change. Thawing permafrost will continue to accelerate the relative amounts of

Box 2.2. Energy



After Serreze et al. (2007).

Solar energy powers Earth's climate system. The phase changes of H_2O, fluxes of currencies and currency interactions are all originally driven by the Sun's radiant energy. For the globe as a whole, on a mean annual basis, Earth absorbs about 240 W m^{-2} of energy as solar radiation. In a steady state climate, the surface and atmosphere together emit the same amount of energy to space as longwave radiation. However, differential solar heating between low and high latitudes gives rise to a circulation that results in a poleward convergence of atmospheric energy transport (Figure 2.1). Because of this transport, in the higher latitudes more longwave radiation is emitted into space from the surface and atmosphere than is absorbed as shortwave radiation. In the annual mean, the energy content of the Arctic atmosphere is approximately constant. For a column extending over the Arctic Ocean, on average, there is a poleward convergence of atmospheric energy transport of about 84 W m^{-2} yr^{-1} and a net annual radiation loss at the top off the atmosphere of about 115 W m^{-2}. The difference between these two numbers is partly accounted for by an estimated net surface energy flux from the ocean to the atmosphere of about 11 W m^{-2}, but cannot be fully reconciled based on existing information. The seasonal cycle of atmospheric energy storage is strongly modulated by the net surface flux, which is also the primary driver of seasonal changes in heat storage within the Arctic Ocean. The July net surface flux of about 100 W m^{-2} (into the ocean) exceeds the atmospheric energy transport convergence. During winter, oceanic sensible heat loss and sea ice growth yield an upward (to the atmosphere) net surface flux of 50–60 W m^{-2}. Because of imperfect data, closing the energy budget of the Arctic Ocean (Serreze et al., 2007) has yet to be fully achieved.

surface and subsurface water flows of dissolved organic carbon, mercury, nitrogen and other biogeochemical materials to the rivers and lakes (Frey and McClelland, 2009).

These biogeochemical feedbacks move into the domain of the biology that affects fisheries, potentially harming human health and triggering transitions to different ecosystem states. Once materials are delivered to the Arctic coastal zone, new interactions among the energy, water, and carbon currencies translate into a broad range of changes to biogeochemical processing, food web functioning, and ecosystem services. Our understanding of how these many geomorphological, physical, photochemical, and biogeochemical processes are linked within the Arctic system is admittedly highly incomplete at this time.

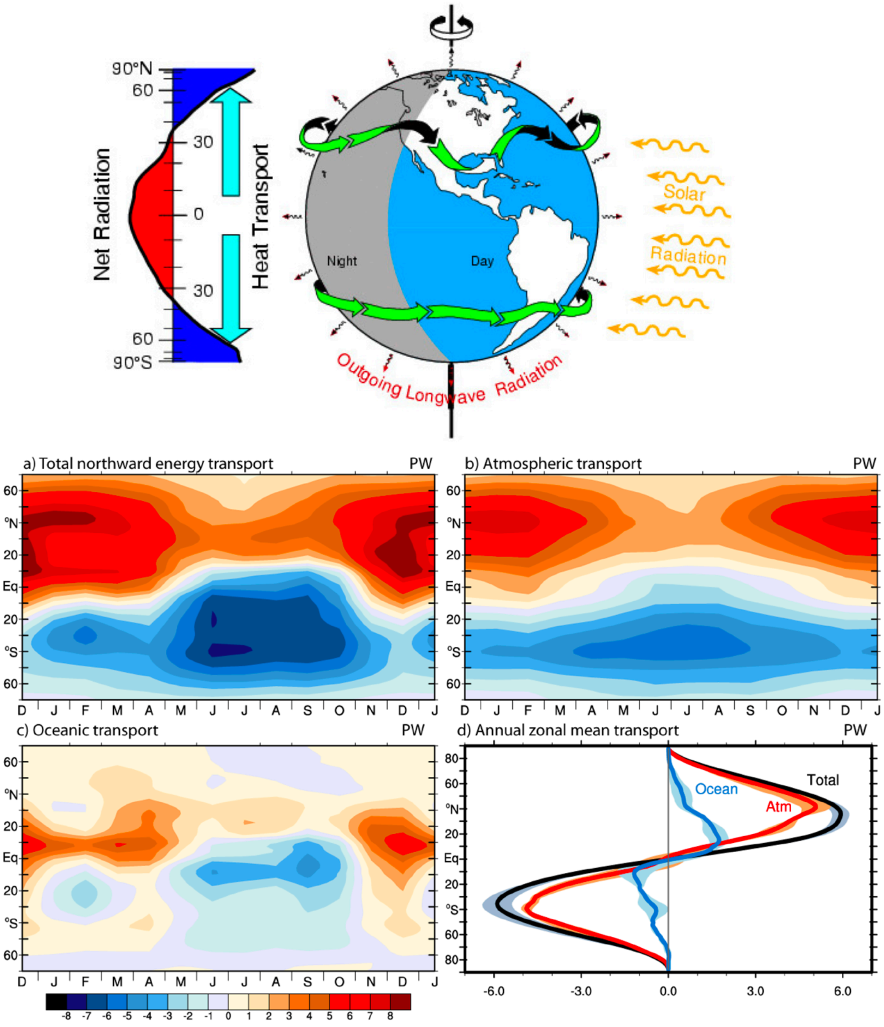


FIGURE 2.1. (top) The poles as critical planetary radiators. Differential solar heating between low and high latitudes gives rise to a circulation of the atmosphere and ocean that transports energy accumulated in the lower latitudes poleward. Once introduced into the Arctic domain, this transported energy then interacts with a large number of processes (Figure 1.1), including strong seasonal freeze-thaw; permafrost thaw; differential land, Greenland ice sheet, and ocean heating; cloud feedbacks; biological responses, for example, the greening (or *shrubification*) of high-latitude tundra. Top image courtesy of K. Trenberth; bottom from Fasullo and Trenberth (2008), reprinted with permission, American Meteorological Society.

2.2. Currencies Behave Uniquely in the Arctic

The geography of the Arctic is distinct: It has a seasonally ice-dominated ocean, well-bounded by land, and constitutes one of the largest land-to-ocean contributing drainage systems on the planet (Vörösmarty et al., 2000). This geography reflects complex linkages among the land, atmosphere, and ocean subsystems, which in turn define how each of the currencies is ultimately distributed over space and time and how it participates in tandem with other currencies to define larger system behaviors. As described in Section 2.1, differential solar heating between low and high latitudes gives rise to a critical circulation of the atmosphere and ocean that transports energy poleward and ultimately discharges most of it back into space (Figure 2.1).

Contributing to this primary planetary-scale phenomenon—which has an absolutely essential dependency on system states in the Arctic—are subsidiary processes involving atmospheric heat and vapor transport; sea ice creation, melting and export; ocean circulation redistributing water and ice; and vertical heat flux through both atmosphere and ocean. Seasonal snow storage is a prominent element of the Arctic climate system and arguably the definitive driver of terrestrial hydrological fluxes. Continental-scale storage of heat and water in Arctic snowpack and the presence of ubiquitous surface water storages (i.e., lakes and wetlands) act to enhance but also buffer atmospheric energy and water anomalies as they propagate through the land-atmosphere-ocean system.

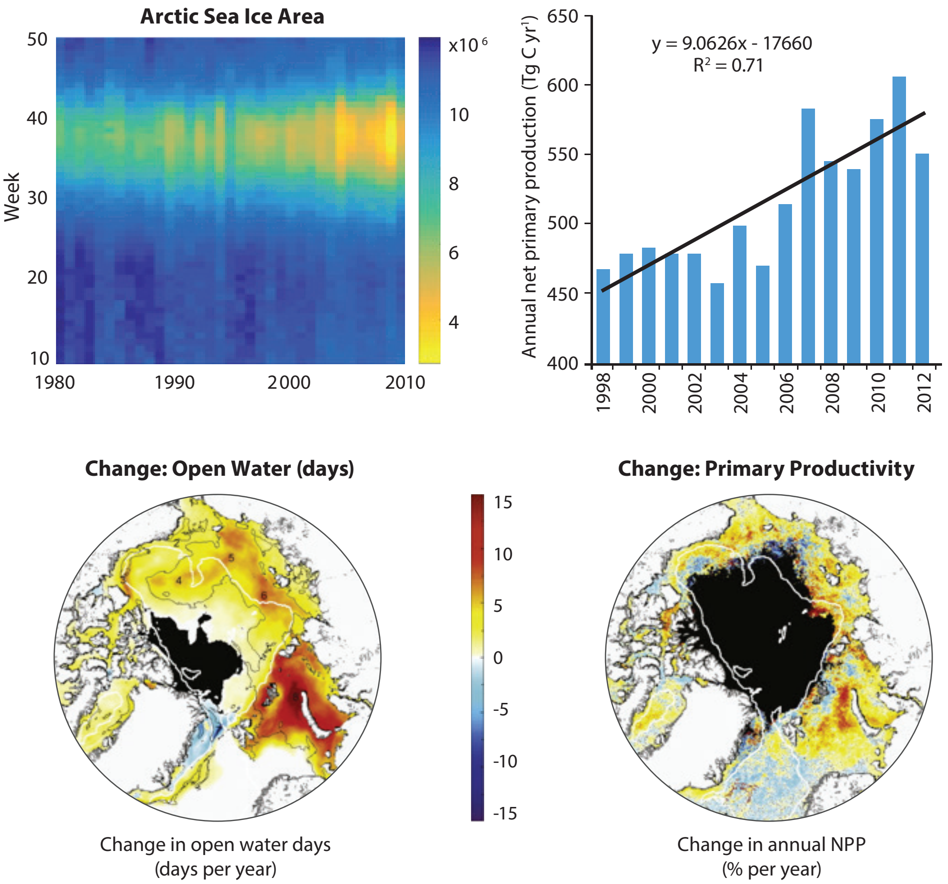
Seasonal freeze and thaw of arctic soils is another unique and critical element of the Arctic climate system. Progressive warming of the pan-Arctic is altering the timing of freeze-thaw transitions, which is a central control on the northern latitude climate. And, coordinated changes have been detected over the entire pan-Arctic domain (McDonald et al., 2004), bearing important implications on energy and carbon storages as well as fluxes. Geomorphological changes in water flow paths accompanying permafrost thaw make it more challenging to anticipate how fluxes of water-borne constituents to the coastal ocean will change in the future (Frey and Smith, 2005; Frey and McClelland, 2009; Vonk et al., 2015).

The Arctic Ocean is also home to a unique interplay of physical, chemical, and biological processes linking its disparate sub-components. Terrestrial inputs of nutrients and organic matter, through river runoff and groundwater seepage, are growing along with increased river runoff, thawing permafrost, and increasing coastal erosion (Roland et al., 2010). This helps to fuel local biological production that is defined by the interactions within the carbon and nitrogen cycles, including nitrification, respiration, and denitrification. These all linked closely to ocean circulation patterns that also determine the presence or absence of sea ice, the quintessential feature of the Arctic Ocean that defines the availability of heat and light (**Figure 2.2**). Coastal erosion is accelerating as a result of elevated wind fetch and wave action associated with

Box 2.3. Water

Water is essential to sustaining life, and on Earth it is unique in its abundance in all three states—solid, liquid, and gas. A majority of Earth's water is stored as a liquid in the world ocean (97.5%), which cover 70% of the planet's surface. Of the 2.5% freshwater, about 69% of that total is frozen freshwater in glaciers and ice caps (Shiklomanov, 1993). The cryosphere is one of the most important components of the Earth system and the Arctic is home to a significant domain of frozen water, due to its role as a thermal energy sink and reflector of incoming solar radiation, and the cycling of water between Earth's land, ocean, and atmosphere reservoirs is intimately coupled with both energy and carbon currencies. Evaporation from the ocean carries with it enormous energy transfer in the form of latent heat. Water is exchanged between the lower latitudes and Arctic system via atmospheric and oceanic transports. On an annual basis, the atmosphere transports about 4900 km^3 of water into the combined terrestrial and ocean domain of the Arctic. Freshwater export from the Arctic Ocean to the North Atlantic is dominated by transports through the Canadian Arctic Archipelago (35%) and via Fram Strait as liquid (26%) and sea ice (25%) (Serreze et al., 2006). The Arctic Ocean is strongly affected by freshwater delivered from rivers (38% of total annual input). Inflow through Bering Strait (30%), and net precipitation (24%) also contribute. Potential freshening of North Atlantic waters due to Arctic sea ice melt, meltwater from glaciers and ice sheets, and precipitation increases and associated changes in density driven overturning is one mechanism by which the action of water currency changes in the Arctic system may influence regional or potentially global climate outside the northern latitudes (**Box 2.1**).

FIGURE 2.2. Biological responses to changing ocean physics are an example of how change in one Arctic subsystem propagates into another. Here, the expanding seasonally ice-free zone opens the door to more light and nutrient inputs, elevating algal production and changing the system from a predominantly benthic-dominated (bottom) to one characterized by pelagic (open water) processes. The ecosystem and nutrient cycles are being reorganized, raising the possibility that northern fisheries will expand into previously unavailable Arctic areas. From R. Newton, Columbia University; Polyakov et al. (2017); reprinted with permission, AAAS; Arrigo and van Dijken (2015), reprinted with permission, Elsevier.



Change in open water days (days per year)

Change in annual NPP (% per year)

changing weather and loss of sea ice that previously played a protective role but are now releasing land-based constituents into the water column. Vertical fluxes in the ocean that carry both water and constituents are defined by mixing and Ekman transport. Stratification modulates these nutrient fluxes and helps establish vertical reservoirs. Most particulate organic carbon (POC) is recycled in the water column. The combined effect of these processes translates into approximately 10% of Arctic ocean primary production being buried in shallow waters, with 1% reaching the benthos over the deep, pelagic, basins.

2.3. Currency "Shutdowns" and "Re-Boots"

Seasonality is a defining feature of the Arctic system, affecting all of its principle elements. Seasonality over land leads to accumulation of water in the form of snow, its melt in the springtime, and high rates of evapotranspiration in the warm season. Linkages among the currencies of energy, carbon, and water are also evident during the seasonal greening-up of Arctic environments. Here carbon is exchanged vertically between the atmosphere and land, and this process reboots in spring when photosynthesis becomes active and sequesters carbon within terrestrial ecosystems, when plants respire and when organic matter is decomposed.

The high latitude reaches of North America are getting greener (Tape et al., 2006), a development possibly related to temperatures that are warming faster in the Arctic, which in turn has led to a longer growing season and other changes to the soils that are favorable to primary production. Warmer spring and summer temperatures are leading to a shorter duration of snow cover as well as to shrub encroachment and densification (Myers-Smith et al., 2011). Both these changes produce a decrease in land surface albedo, a positive feedback that reinforces warming. Future changes in the spatial distribution of vegetation is projected to alter albedo, energy balance, nutrient, and carbon budgets (Kaplan et al., 2003; Sitch et al., 2008). The Arctic's broad-scale tundra greening, recently transformed to "browning," requires an understanding of permafrost-water relations, plant-herbivore interactions, the trapping of blowing snow and an interpretation of how these macro-system changes relate to ecosystem responses to heating in experimental microcosms (Epstein et al., 2016). While greening and browning are detected at the surface, the carbon captured by plants during photosynthesis is buried and entrained into subsurface processes. Questions then arise as to what degree belowground processes (e.g., microbial decomposition) offset any carbon gains from greening, which in turn are linked to the manner in which the physics of the permafrost is changing (e.g., active layer depth, temperature, thaw).

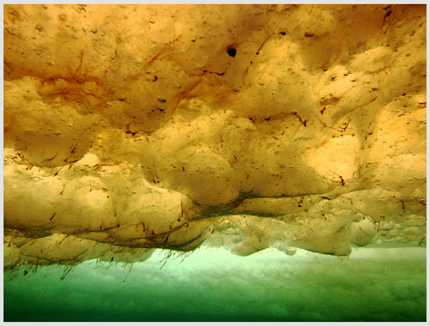
An analogous process occurs in the Arctic Ocean, with strong seasonality controlling production and biologically mediated carbon exchanges in the marine ecosystem. Seasonal changes in ocean net primary productivity (NPP), its magnitude, and vertical extent arise from variations in temperature, light, nutrient availability, and physical forcing, as well as associated planktonic and sea ice food web processes (Lee et al., 2016). The seasonality of sea ice growth and melt plays a dominant role in the productivity of a system that has been primarily light-limited (Arrigo et al., 2008). Beneath the perennial ice cover, which historically extended over seven million square kilometers, nearly the entire area of the deep Arctic ocean basins, about half the biomass was within a meter of the ice-ocean interface. However, with the warming of the Arctic, the seasonally ice free zone is expanding northward, bringing light to the central Arctic ocean surface and shifting the system to one that is nutrient-limited, and in which open ocean productivity dominates. In this context, the research community has recognized the need to quantify the roles of both environmental and ecological controls on NPP in the heterogeneous, rapidly-expanding and seasonally ice-covered Arctic Ocean.

Box 2.4. Carbon and Nutrient Biogeochemistry

Carbon and other biotically active elements are connected to living things by a broad range of biogeochemical processes, linked very closely with the cycling of water and energy. Human disturbance of the carbon cycle in Arctic biomes is increasingly defining the character of the full Arctic system through its close connection to pan-Arctic energy, water and biogeochemical balances and thus the behavior of a linked system.

The atmospheric concentration of CO_2 is currently at its highest value (410 ppm) for the last two million years (Tans, 2018). Globally, terrestrial ecosystems store approximately 3170 gigatons (1 GT = 1 billion metric tons) of carbon, with nearly 80% (2500 GT) in soils (Lal, 2008), more than three times the atmospheric pool of 800 GT (Oelkers and Cole, 2008). Carbon stored in plants and animals is comparatively small, while the ocean contains the largest amount (~38,000 GT), mostly as dissolved inorganic carbon (DIC) (Houghton et al., 2007). Despite the low inputs of precipitation (much of the Arctic, with less than 25 cm/yr of precipitation is technically desert), the Arctic hosts extensive wetlands and deep, organic-rich permafrost. Cold temperatures maintain this efficient depository for the carbon currency over thousands of years, and a massive "bank account" of organic carbon has accumulated in Arctic ecosystems over many millennia, with approximately 1672 petagrams (Pg; 1 Pg = 1 GT) (Schuur et al., 2008), in soils, mostly locked in permafrost.

Warm temperatures, caused by human activity, release this geologically stored carbon into the Earth system as a currency flux, which boosts atmospheric carbon stocks, chiefly as CO_2. Land-based disturbances such as permafrost thaw and fire further impact the flow of carbon and materials between the region's vast biogeochemical reservoirs. Arctic lands and oceans at present are a net CO_2 sink of 109 Tg C yr^{-1} (McGuire et al., 2010). Terrestrial areas of the Arctic Basin annually lose 62.9 Tg C yr^{-1} to the Arctic Ocean via rivers, with the Arctic Ocean gaining 94.1 Tg C yr^{-1} through riverine inputs and as CO_2 from the atmosphere. Primary production in the Arctic Ocean, including ice-associated algal production and new open water productivity, support all marine life and food chains, and are thus intimately connected to atmospheric CO_2 concentrations by way of the air–sea interface.



(above) Thawing permafrost. Credit: David Houseknecht, USGS.
(right) Sea ice algae community. Photo courtesy of Andrew Thurber.

2.4. The Legacy Effects of Previous Currency Processes

The Arctic's largely frozen state has made the signatures of earlier physical, chemical and biological activity highly evident. These antecedent signals take the form of currency storages, like those that sequester carbon or water for often long periods of time as they reside in permafrost, ice sheets or glaciers. For example, fixed carbon has accumulated belowground at high rates in arctic environments, pre-dating the Holocene period since the most recent ice age. Organic matter decomposition that releases this carbon is influenced by plant and microbial inputs as well as microbial-mediated transformations in soils, but it is predominantly cold temperatures that limit decomposition in relation to primary production (Figure 2.3). Carbon inventories suggest that the terrestrial Arctic stores over 1000 Pg of carbon in the upper three meters of soils (Hugelius et al. 2014), with even greater stores residing below this depth (1330–1580 Pg C of known stored deposits; Schuur et al., 2015).

Such legacy stores of energy, water, and carbon, if liberated, have the potential to yield substantial impacts on future Arctic environments and global society, even in the near-term. These impacts are determined largely by environmental controls—soil temperature and moisture content—two elements of the modern Arctic that are today changing rapidly. In fact, based on various approaches such as incubation studies, dynamic models and expert assessments, it is projected that between 5% and 15% of soil carbon may be vulnerable to greenhouse gas release to the atmosphere by the end of the century, thus representing a potentially substantial positive feedback on planetary warming (summarized in Schuur et al., 2015). The release of methane from organic soils represents yet another globally significant concern regarding the release of that radiatively important gas, whose greenhouse warming potential is much greater than that of CO_2 on shorter timescales (Lashof and Ahuja, 1990, Boucher et al., 2009), ~40 times higher on a molar basis prior to its oxidation in the atmosphere (Alvarez et al., 2012).

In the ocean, ancient carbon deposits are present under the sea floor, particularly in shelf regions. Methane naturally forms as organic matter decomposes in these environments. In the cold Arctic Ocean methane can become trapped,

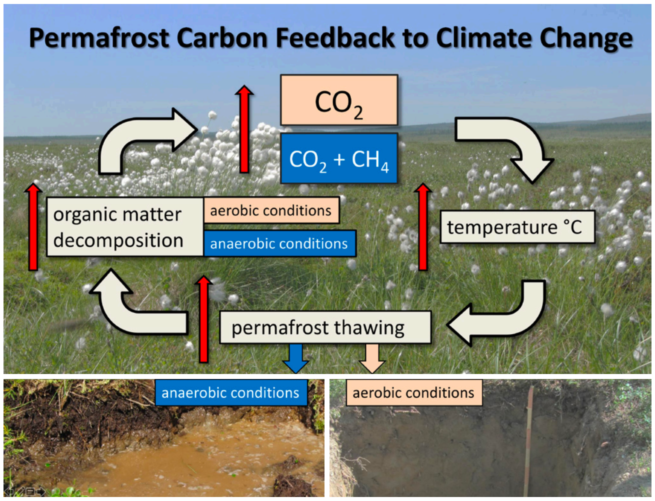


FIGURE 2.3. Permafrost carbon feedbacks to climate change include both physical processes as well as the biogeochemistry of aerobic and anaerobic environments. Huge stocks of carbon, particularly, as methane, could be released under conditions of thawing permafrost. Given rapid observed losses in permafrost across the Arctic (ACIA, 2004; Romanovsky et al. 2010a, 2010b; Smith et al., 2010), the time horizon of this feedback is the imminent future. Image courtesy of C. Schädel.

Box 2.5. Linked Currencies

Research on the coupling of currencies helps us to better understand how the Arctic functions as a unified system. For example, feedbacks between temperature and water vapor may be contributing to amplified warming in the arctic atmosphere, but this feedback is not fully appreciated due to uncertainties in changes in cloud properties that arise from an overall warmed state of the atmosphere, which can hold more vapor and cloud condensation nuclei. A deeper understanding of interactions among climate warming, hydrological cycle intensification, and permafrost thaw is also needed to better predict future impacts to land-ocean carbon and material exports. Arctic rivers convey large fluxes of carbon, sediment, and other constituents to coastal zones and the ocean at large. Energy, water, and carbon flows in the Arctic Ocean, in turn, are important controls on biological productivity for marine species and ocean circulation, the latter of which influences the movement of sea ice and freshwater with the basin. Arctic river waters warmed by solar energy transmit this heat as they exit the land mass and in doing so impact ice melt in the coastal zone, which in turn influences carbon and nitrogen cycling, microbial and metazoan community composition, and trophic relationships. These are a few of the many examples demonstrating how currency linkages play themselves out within a complex Arctic climate system.

freezing into methane hydrates. An increase in temperature can cause these hydrates to destabilize and release the methane in large quantities (Archer, 2007; Shakhova et al., 2005, 2010). Though large-scale release of these methane hydrates into the atmosphere is thought to be unlikely, evidence of a large methane leak at once over a large region dating back around 110 million years (Williscroft et al., 2017) raises the possibility that anticipated warming over the next decades could cause a similar event. The Arctic would then produce a critical and potentially catastrophic methane-generated heat burden, by reactivating an otherwise frozen, essentially inert stock of legacy carbon into the modern atmosphere.

2.5. Currency Exchanges Dampen or Amplify System Dynamics

Currencies can be thought of as gears spinning at different speeds, interacting with each other, and with different levels of inertia. The complex mechanics of such a machine mean that different currencies will contribute to accelerating or slowing the pace of change. Hydrologic processes within Arctic river basins, for example, are tightly coupled with local soil conditions and serve as an important control on the rate of permafrost thaw and soil carbon decomposition. Without active hydrologic fluxes—themselves liberated by increasing energy inputs—permafrost degradation and carbon losses are substantially delayed and dampened (Liljedahl et al., 2016).

The reverse is also true, and is of concern insofar as climate warming is causing an intensification of the freshwater cycle across the Arctic system, brought about by increases in the water-holding capacity of the atmosphere, increased precipitation, evaporation and runoff. This trend is anticipated to continue (**Figure 2.4**, Shkolnik et al., 2018). Along with this hydrologic acceleration (Rawlins et al., 2010) comes an increase in the frequency and strength of extremes, giving changes to the water currency a pivotal role in modulating the land surface energy balance, permafrost integrity and carbon storage.

Observations point to intensification of heavy precipitation events in recent decades, yet simulated projections for the future cannot be fully anticipated and, in fact, may be underestimated given the low biases in models simulating heavy precipitation events (Dai, 2006). Nevertheless, extreme events (described in more detail in **Chapter 3***)* can be used to better understand the capacity of the Arctic system to dampen or accelerate large-scale currency dynamics. Record high river discharge from the Eurasian landmass in 2007, for example, has been traced ultimately to moisture transport from the North Atlantic and unusually high snow storage, anomalously high heat transport into the region and subsequent rapid melt (Rawlins et al., 2009b)—all representing an amplification of the hydrologic cycle due to a changing energy balance.

The temporal aspects of such currency dampening and intensification are complex. For the terrestrial Arctic (other than northeastern Asia), strong warming is expected to cause decreases in spring snow storage, thus changing the normal timing of freeze-thaw and the potential speed with which liquid water derived from precipitation is transported via rivers. Here, the disappearance of a stock of frozen water, important for delaying and dampening fluxes intrinsic to the cryosphere, has been diminished in importance as a result of energy currency change conveyed through the atmosphere. Climate

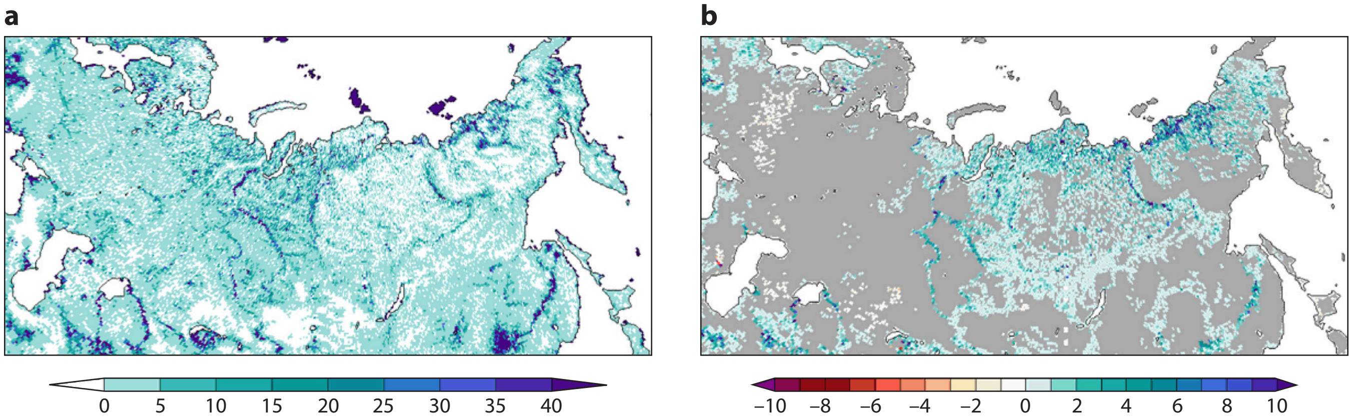


Figure 2.4. Anticipated increases in northern Eurasian River discharge changes the spatial pattern of flood hazard. Fraction (%) of spherical grid box (0.25 °× 0.25°) covered by mean annual maximum flood in the (a) baseline period (1990s) and (b) projected changes of the fractions by 2050–2059 as simulated by RCM30–CaMa-Flood under IPCC RCP8.5 scenario. Values are masked in gray where the signal-to-noise ratio is less than 1. The models project an increase in flood hazard across much of central and eastern Siberia, with a decrease projected across southwestern areas in spring. From Shkolnik et al. (2018); reprinted with permission, Springer.

models project that extremely high winter precipitation, with more liquid component (Groisman et al., 2006), will increase over large areas of the high latitudes of North America and Eurasia, with consequent amplification of climate-normal water fluxes. These models also point to an increase in flood hazard, primarily in the central and eastern Siberia, and the Far East, with decreases projected in the southwestern areas in spring (Figure 2.4).

Tracking currencies is also useful in demonstrating how feedbacks arise, for example in potentially amplifying warming. Permafrost stores substantial quantities of ancient carbon that could be released into the modern atmosphere with catastrophic radiative effects. Arctic peatlands lose nearly one-third of their below-ground carbon following permafrost thaw in a matter of decades. This suggests that phase changes associated with water as the climate warms could be the genesis for an important feedback to modern climate through the release of ancient, though nonetheless radiatively significant, carbon stocks. Post-thaw bog carbon accumulation (a dampening) recuperates some carbon losses, but this can take millennia for older peatlands, though much less time for younger peatlands (Figure 2.5). Permafrost landscapes are highly fragmented systems and are at different stages of thaw, indicating that the ultimate nature of such a feedback will be difficult to forecast, and that many other phenomena in the Arctic constitute a critical systems-level unknown.

Systems-level research studies are needed, then, to better understand the top-down impact of permafrost thaw on the global carbon cycle and the timescales over which they alternatively can serve as sources but also sinks. The Kenai Peninsula in Alaska has experienced a 60% loss in permafrost plateau extent since 1950 (Jones et al., 2016), highlighting the vulnerability of permafrost carbon stores at the southern limits of modern permafrost extent. One modeling study, which included permafrost carbon dynamics, projected that Arctic terrestrial ecosystems north of 60°N could shift from being a CO_2 sink to a source by 2100, and potentially mobilize 85 ±16 Pg C (Koven et al., 2011). Over the Holocene, thermokarst lakes, while initially sources of carbon, have accumulated carbon and served as a net carbon sink (Walter Anthony et al. 2014). Permafrost in lowland areas often results in semi-well-drained plateaus evolving into an inundated fen or bog. Leaching rates of dissolved organic carbon flux from these landscapes tend to be higher in the very young collapse-scar bogs, which also have the highest methane production potential (Treat et al., 2014). Based on belowground mass-balance carbon accounting, young collapse-scar bogs lost carbon most rapidly, a process that slowed with time since thaw, leading to a return of the system to a net carbon sink centuries to millennia after thaw (Jones et al., 2017). Winter carbon fluxes are yet another, less well-quantified process, requiring further study. These many processes remind us that water-energy-carbon interactions are in a constant state of flux, with some of the processes dampened while others are accelerated.

When energy is transferred into glaciers and ice sheets, ice-to-water phase change starts to accelerate, mobilizing liquid water. One critical concern is how the melting of the Greenland ice sheet proceeds as an ever-cascading acceleration—with meltwater collecting on the surface breaking through with the formation of moulins, which then discharge water downward, increasing melt at depth but also potentially "lubricating" the bottom boundary of the system (Zwally et al., 2002; Joughin et al. 2008). Whatever the specific mechanism, the net result is a rise in sea level with planetary-scale implications. Total

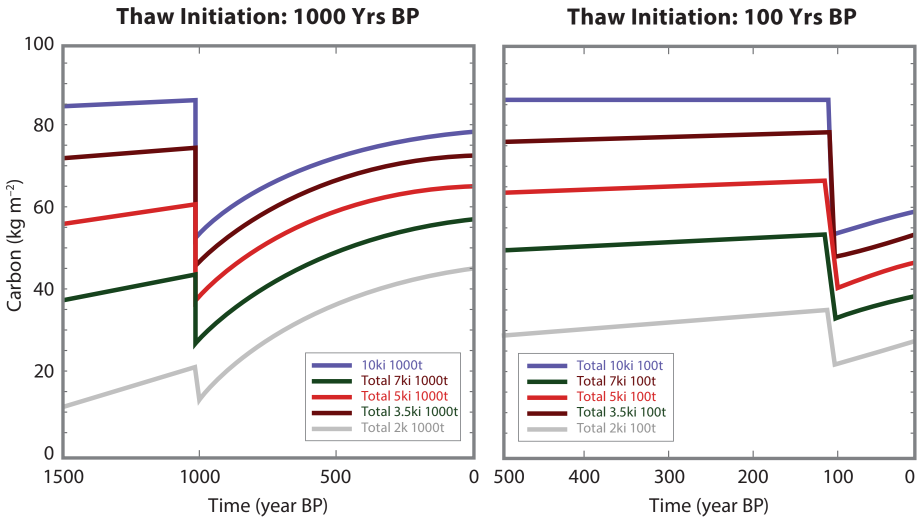


Figure 2.5. Legacy effects and ages of landscapes need to be accurately mapped insofar as they have critical differences in greenhouse gas emission potential. Time series show carbon stocks (kg m^{-2}) since time before present (BP), with each plot representing a different time that thaw begins relative to the present. Each curve represents a different peatland age. These experiments show that the oldest peatland is never able to recuperate its carbon losses, while the youngest manages to recover the losses in several decades to centuries. Integrating in three dimensions is necessary to achieve pan-Arctic inventories and to calibrate and validate models of these processes. After Jones et al. (2017).

glacier and ice sheet ice and water flux into Arctic Basin are very poorly constrained, but appear to be large and increasing in response to Arctic amplification. Glacier net inflow to the Arctic Ocean, specifically net glacier volume loss, has been comparable to the combined river net inflow from the largest pan-Arctic rivers. Since the 1990s, freshwater inflow data show substantial and similar patterns of increase from rivers and glaciers. It is likely that this increase is a response to climate warming and an increase in annual precipitation in the 50°–70°N latitude band in North America and Eurasia (Dyurgerov and Carter, 2004).

2.6. Geomorphological Controls on Currency Distributions and Fluxes

The spatial organization of landscapes, coastlines, and the ocean bear important implications for the ways in which the currencies that they contain function. This organization is critical in determining a fundamental feature of the Arctic system: that is, land-to-ocean fluxes and how water, energy and constituents are mobilized, transported and finally delivered into oceanic receiving waters. For example, a recent synthesis of data from stream/river systems differing in size by

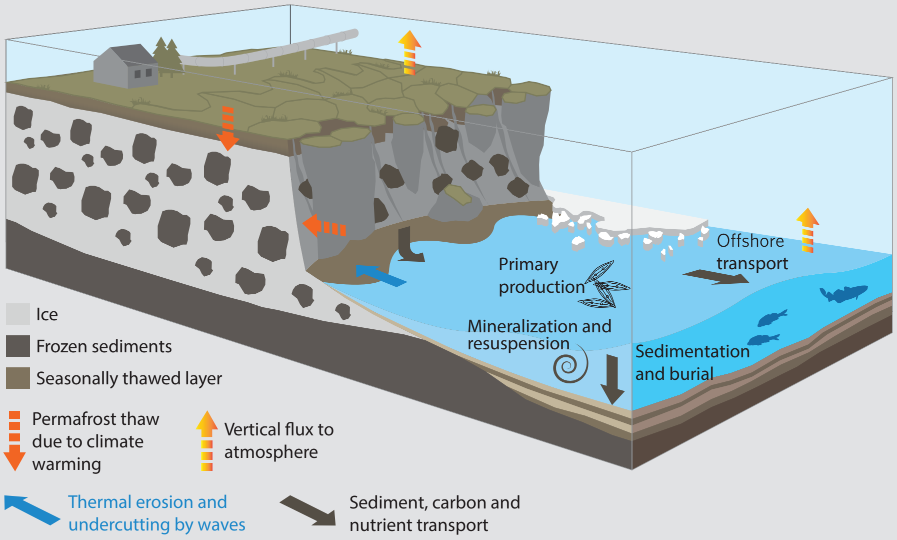
Box 2.6. Currencies Where the Land Meets the Ocean: The Coastal Arctic

The Coastal Arctic is defined here as the interface, boundary zone, or continuum between land and ocean characterized by important currency fluxes to and from each of the two domains. The physical dimensions (i.e., width) of the coastal zone are characterized by the timescales that are associated with currency transfers. Arctic coastal regions are known to be productive environments, where constituents and energy derived from large land and ocean domains are concentrated and, at least temporarily, stored in biodiverse deltas, estuaries, or ocean valleys (Fritz et al., 2017). Arctic coastal estuarine systems are highly productive and serve as carbon and nutrient sources to the coastal shelf areas and adjacent seas, fueling food webs and fisheries. Accordingly, it is the coastal domain that many of the Arctic people call home.

The heterogeneous nature of Arctic coastal areas, which typically include complex deltas and barrier islands, produces a highly variable network of water and carbon exchanges as compared to lower latitude coastal areas. These comprise a quintessential complex system. At the same time, coastal system fluxes are changing rapidly and give rise to important systemic changes, for example, the loss of sea ice leading to increases in wind fetch that produce coastal erosion, which in turn, stimulates the loss of trapped carbon stocks or destruction of coastal infrastructure.

The Arctic coastal zone as well comprises an important "intellectual interface" where answers to basic research questions take on an urgency in applied research. In both research domains this will require addressing questions that extend beyond traditional disciplinary bounds and a synthesis approach. For example: *Will the size of the coastal zone geographically change in a warming Arctic, in association with indirect climate changes, or associated with direct anthropogenic interaction (i.e., coastal reclamation)?*

(above) Wetland and low relief tundra habitats of the Arctic coastal plain. Photo credit: USGS. (right) From Fritz et al. (2017); reprinted with permission, Nature Publishing Group.



three orders of magnitude across the pan-Arctic suggests that watershed slope may serve as a master variable controlling dissolved organic matter (DOC and DON) flux concentrations (**Figure 2.6**). DOC and DON concentrations both show strong negative correlations with watershed slope, reflecting the contrast of organic matter accumulation in lowlands versus uplands. Nitrate concentrations are also correlated with watershed slope (in this case positive), but this relationship is much weaker.

While our overall understanding of fluvial export from land to sea in the Arctic is improving, we still need to learn more about nutrient and organic matter cycling within river networks to support process-based modeling of riverine fluxes. The research community is well-poised to employ biogeochemical modeling to understand currency exports across ungaged/unmonitored regions. However, for modeling studies, rates of photo-degradation and biological processing (e.g., conversion from DOC to CO_2 efflux) in streams is a key unknown that precludes up-scaling of measurements to estimate regional and continental exports. A strong positive linear relationship between DOC concentration and CDOM absorption has been observed, presenting the potential to use optical remote sensing measurements to improve understanding of DOM dynamics in fluvial systems (Mann et al., 2016; Griffin et al., 2018; **Figure 2.6**).

These observations and modeling studies suggest that the Arctic system has some convergent properties that organize themselves around currency dynamics. Geomorphology has been the subject of numerous systems analysis and scaling studies over the years (McNamara et al., 1999; Zarnetske et al., 2007; Greenwald et al., 2008). These have revealed watersheds and the rivers draining them to be complex topological networks, with predictable properties and dynamics. These recent results from the Arctic suggest a similar potential predictability, but a definitive answer would need to consider the distinctive character of the Arctic system and its component ice, snow, frozen wetland and permafrost dynamics, and in particular the impact of warming these subsystems. This constitutes a major research challenge and one that is intrinsically systemic in its nature.

The geomorphology of the Arctic coastal zone is also an important determinant of currency behaviors, with permafrost along coastlines a ubiquitous element of the landward edge of the Arctic Ocean. Rapid environmental changes that are occurring in the Arctic nearshore zone are under-studied because of highly imposing logistical constraints. However, the effects arising from a lengthened thaw season, declining ice cover, enhanced wave action due to storms, and sea level rise are anticipated to increase rates of coastal erosion. Research is needed to understand how changes in the geomorphology of arctic coastal areas is impacting the key currencies within

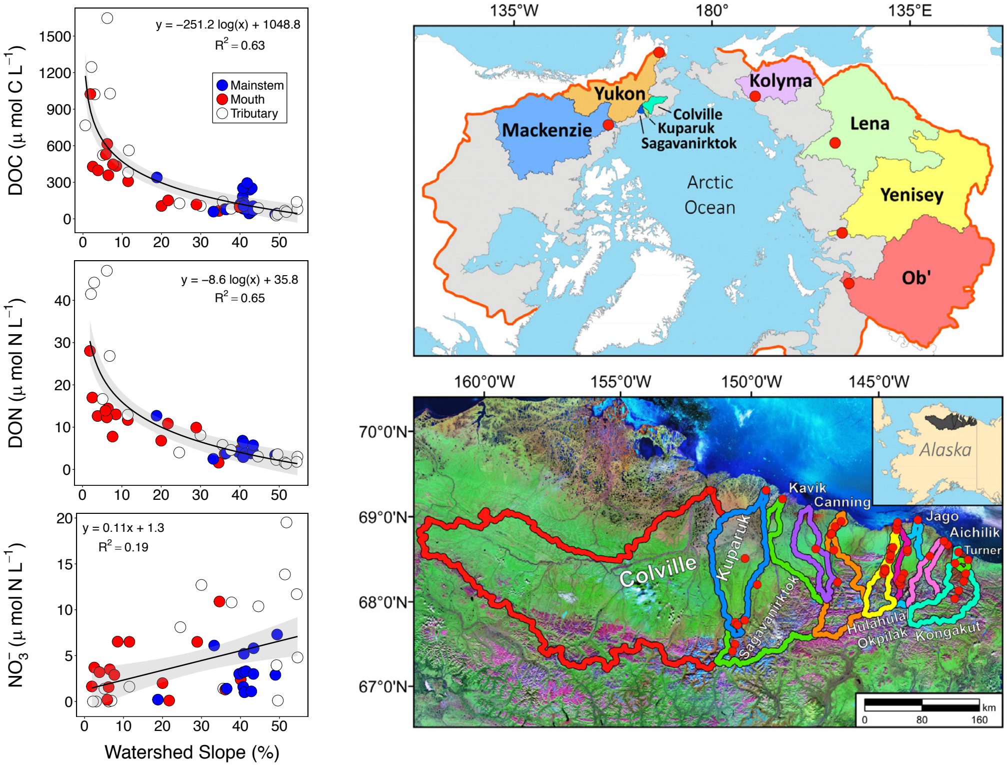


FIGURE 2.6. Evidence for geomorphological control (i.e., watershed slope) of dissolved organic matter and nitrate concentrations in Arctic rivers (left). Watershed slope predicts the concentrations of these important biogeochemical constituents across a wide range of spatial scales and geographic locations. Data for the slope-concentration relationships were drawn from the six largest rivers in the pan-Arctic watershed (top right) as well as numerous smaller rivers draining the North Slope of Alaska (lower right). Dots in the right-hand panels mark sampling locations on each river. From Connolly et al. (2018); reprinted with permission, American Geophysical Union.

Box 2.7. Currencies in the Ocean Domain

In the Arctic Ocean, the preeminent currency of water carries with it other currencies such as energy and carbon. The Arctic freshwater budget is not restricted to an accounting of freshwater on land or atmosphere but also in the ocean, which maintains complex exchanges. Arctic freshwater has a large store of internal energy (energy related to its temperature) which varies seasonally, largely through energy exchanges at the ocean surface. The total energy of the Arctic Ocean also varies through the formation and melt of sea ice (exchanges of latent heat energy). At the same time, the Arctic Ocean gains internal energy largely through the import of Atlantic waters and from the Pacific through the Bering Strait. River discharge adds water mass and some internal energy to the Arctic; in a steady state the mass gain must be balanced by outflows, largely through Fram Strait and the channels of the Canadian Arctic Archipelago. At the same time, river input represents a key source of dissolved carbon to the system. River input, oceanic water inflows and outflows, and net precipitation also control the Arctic Ocean's freshwater budget, and freshwater (or, alternatively, salt) can be viewed as an additional currency. There is mounting evidence that energy storages in the Arctic ocean (internal and latent heat) and freshwater inputs and outputs are changing, which are distributed throughout the Arctic system, such as through changes in marine productivity associated with diminished sea ice.

The accompanying diagram presents the annual mean freshwater budget of the Arctic relative to a reference salinity of 34.8 psu. The atmospheric box combines the land domain (the Arctic terrestrial drainage) and the ocean domain. The boxes for land and ocean are sized proportionally to their areas. Transports are in units of km^3 per year. Stores are in km^3. The width of the arrows is proportional to the size of the transports (Serreze et al., 2006).

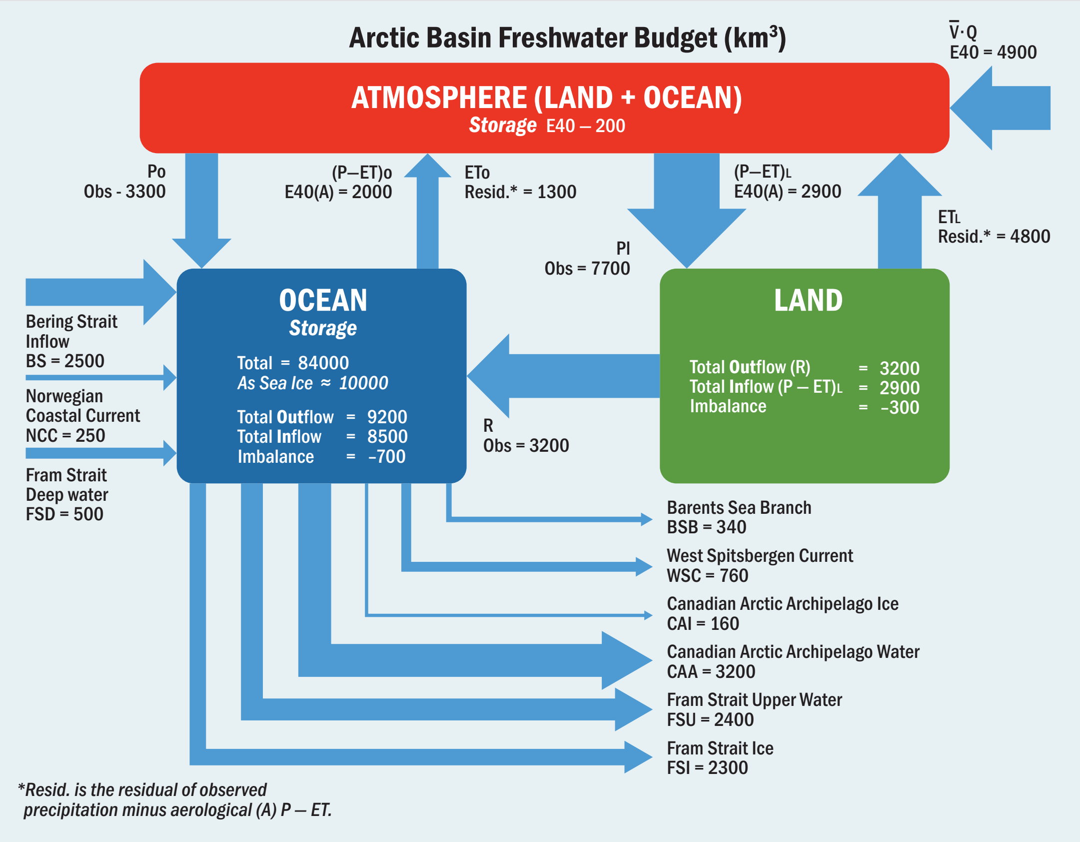


Image after Serreze et al. (2006).

this area, insofar as coastal erosion fluxes have the potential to increase by an order of magnitude over the next century (Zhang et al., 2004) (**Box 2.5**). Such research would necessarily involve analysis of four linked subsystems: (1) the landmass that generates runoff and icemelt, which carries energy, sediment and constituents to the ocean; (2) the ocean with its dynamical processes connected to the presence/absence of sea ice, tides, waves and currents; (3) the atmosphere, which generates wind-wave interactions, is the transport vehicle for energy exchanges associated with thawing or freezing of sea ice and transfers of aerosols and pollutants; and (4) water, energy, and sediment redistributions that configure the geomorphology of the coastal zone itself. This requires, nearly by definition, a systems-level understanding of current states and future changes.

Offshore, coastal shelf geomorphology also exerts controls on currency exchanges and system-level behaviors. Here methane is stored in permafrost hydrates within marine sediments on the relatively shallow shelf in the Arctic Ocean. Because of the shallow depths, these methane reservoirs are highly sensitive to climate warming. Areas adjacent to river mouths may be particularly vulnerable if freshwater runoff warms more than coastal waters. Groundwater flow through coastal sediments represents a possible transport mechanism, which may lead to or enhance the formation of taliks, essentially unfrozen within sub-sea permafrost (Shakhova et al., 2017).

2.7. Currencies in the Applied Research Domain

Here we present three examples of how applied research questions could benefit from an Arctic system perspective that includes currencies.

Potable Water Supply. Understanding the short- and long-term availability and sustainability of the local currency of potable water in remote Arctic communities requires in-depth knowledge of local, regional, and even pan-Arctic water systems, as well as their interactions. For example, risks from air- and water-borne pollutants need to be known because thawing permafrost and increased fire frequency may affect the quality and quantity of potable surface water. At the policy level, decisions will need to be made on how and when to make infrastructure upgrades or whether to build new facilities, including sanitation and sewer facilities. Societal changes must also be taken into account: economic pressures, for example, and population growth and/or decline. Some of the basic knowledge needed to support long-term solutions of potable water projects may be considered relatively “shovel ready.” Basic research on freshwater system and permafrost dynamics have been a major focus of the last 20 years. But general knowledge gaps, including the uncertainties highlighted throughout this chapter, interfere with the downscaling strategies that are necessary to make forecasts that would support planning at the local scale.

Sustaining Populations of Pan-Arctic Caribou and Reindeer. Caribou, an important food source for people in the Arctic, can be seen as a biological currency within the Arctic system. Identifying a sustainable long-term management approach to caribou and reindeer populations constitutes yet another systems-level research challenge. Here water, carbon, and energy currencies are critical environmental determinants of wildlife support systems such as winter lichen and spring cotton grass as food sources, winter shelter, and insect relief. As the climate changes, there must be contiguous access to the resources—and availability at critical times in life cycles. Changes in climate are linked to extremes, such as rain-on-snow events that limit access to forage available to wildlife, and thus threaten humans who are dependent on animals for food and economic livelihood in the region. Readiness to tackle this challenge is dependent on the confidence in estimates of future climate across the region, including the magnitude and frequency of these extreme events.

Contaminants: Human-Engineered Currencies in the Arctic System. As we track changes in physical and socioeconomic currencies, it will be important to learn how changes redefine contaminant sources, transports and uptake (**Box 2.8**). Such knowledge is required to manage the quality of terrestrially based food resources and fisheries, and also to determine and manage ice sheds for vulnerable regions, including marine protected areas (Pfirman et al., 2009). In polar bears and beluga, the PCB concentrations currently exceed the toxicity reference value for immunotoxicity and endocrine disruption (NCP, 2013). Looking ahead, there are “… large uncertainties in understanding the influence of rapid climate change on the fate and mobilization of both legacy and new POPs in the Arctic” (NCP, 2013).

Box 2.8. Currencies, Contaminants, and Transport Processes

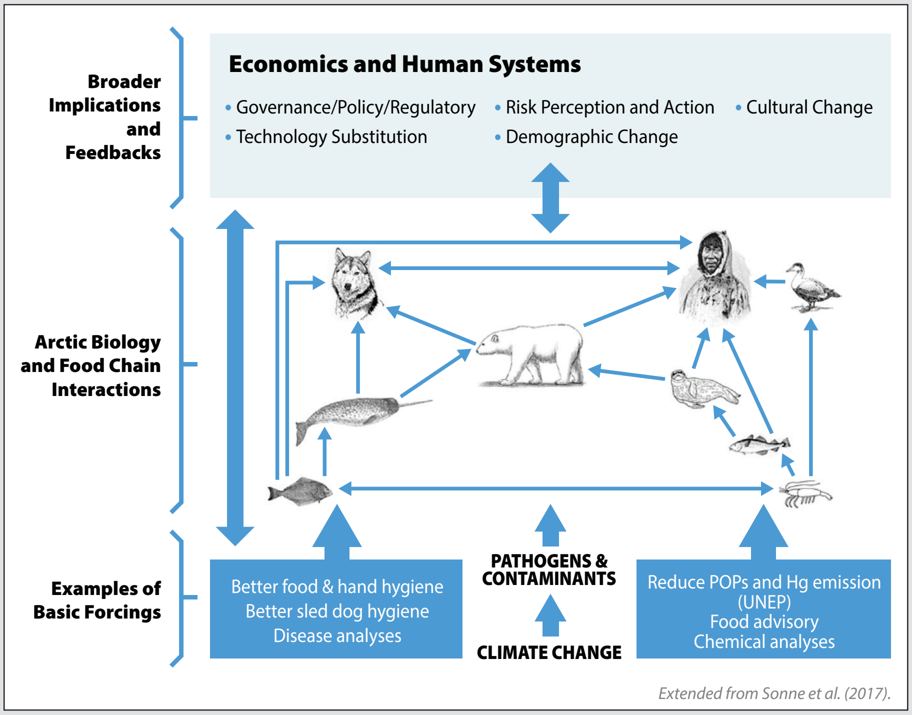
A set of currencies that have been tracked for their detrimental impacts on humans and other fauna are biologically damaging contaminants, such as organochlorines, pesticides, flame retardants, mercury, and microplastics. While not drivers of the physical system as the major currencies addressed in this report, pollutants are critical because (1) some have reached levels in the atmosphere and waterways that threaten healthy ecologies and human health, and (2) they are mainly anthropogenic in origin, and can therefore be addressed through policy choices**.** Like energy, water, and carbon, contaminants cross the boundaries into and out of the Arctic domain, carried by wind, rivers, and ocean currents, as well as by migrating wildlife. Point sources within the Arctic may emanate from oil spills at wellheads or from ships, mines, and smelters, or marine accidents among industrial, fishing, or tourist vessels. As development increases in the future, local sources of contaminants are likely to increase (e.g., Kelly et al., 2010; Darrah et al., 2014). Ongoing and future changes in the other currencies will also affect contaminant distributions and bioavailability. For example, as the Arctic atmosphere warms and sea ice loss becomes more extensive, stored contaminants such as microplastics (Obbard et al., 2014) and organochlorines will be released. Guglielmo et al. (2012) estimate that regional-scale seasonal sea ice melting could double the surface ocean contamination of HCH and DDT.

The Arctic's extreme cold and the presence of sea ice modulate the transport and behavior of contaminants. Cold Arctic conditions mean higher fat content in Arctic megafauna—including humans—than those at lower latitudes. Many pollutants, including organochlorines, are lipophilic, that is, accumulating in fatty tissues as they move up the food chain. Organochlorines in the atmosphere are cold-trapped in the Arctic, and the stable Arctic atmosphere allows locally sourced contaminants to persist. Surface inflows of ocean water from the North Atlantic and Pacific transport marine contaminants into the Arctic.

The transport of multiyear sea ice is one of the few processes that concentrates, rather than dilutes, contaminants (Mackay and Wania, 1995; Pfirman et al., 1995). Contaminants are entrained when sea ice forms, especially in coastal regions, and are also deposited on the ice surface from the atmosphere. Over time, the contaminants accumulate on the ice surface because of melting snow and ice in summer. The entrained contaminants are then released primarily in the marginal ice zone during spring/summer melt. This process injects contaminants at the most critical time and place: during spring/summer when maximum primary production occurs, at the sea surface, and mainly over shelf seas where the likelihood of impacts on humans is greatest.

As the Arctic warms and thinning sea ice becomes more mobile, sea ice exchange between the marginal seas—transnational ice—is increasing (Newton et al., 2017). In the future, more transnational ice will likely melt in the central Arctic, releasing its contaminant load there, with uncertain effects on ecosystems (Pfirman et al., 1995). Amplified Arctic warming also reduces the meridional temperature gradient, which drives the cold-trapping of semi-volatile contaminants in the Arctic. As a result, the jet stream becomes weaker, causing increased blocking patterns and more persistent weather conditions (see Box 3.4). It is not known how these changes will affect atmospheric transport of contaminants.

Like energy, water, and biogeochemical constituents, contaminants are a form of currency. They circulate and are intrinsically connected within the Arctic system. Yet, they have particular characteristics, such as bio-accumulation and important, often direct, impacts on the humans who harvest renewable food resources, that require unique systemic study through observations/monitoring, modeling and experiments to understand pre-conditioning as well as buffers/resilience such as prey switching and implications for governance and better management.



Extended from Sonne et al. (2017).

CHAPTER 3. EXTREMES IN THE ARCTIC SYSTEM

Sources, Impacts, and Reverberations into the Earth System

This chapter addresses how systems-level thinking and synthesis approaches can be used to explore extreme events and what can be learned about systems though focused studies of extremes. Extreme events are typically defined using statistical analysis, but there are certainly exceptions (**Box 3.1**).

From a systems viewpoint, the central questions become: *What are the biogeophysical forces that generate extreme events in the Arctic? How do they function? How do they change over time?* While useful for organizing the dialogue, it was recognized during the First Synthesis Workshop that a suite of derivative questions would also be valuable to pursue (**Box 3.2**). Though it is not the intent of this report to provide comprehensive answers to each, aspects of such questions are considered throughout this chapter.

Four themes relating to extremes are highlighted below. The narrative first describes regime shifts and how these may give rise to extremes, and then goes on to discuss approaches taken by researchers who study such phenomena. A brief treatment of some of the societal implications is given, followed by potential policy responses. A supporting goal is to demonstrate how currencies shape the dynamics of an extreme event and thereby provide a convenient means to track how the appearance of an anomaly in one domain—such as heat transported into the Arctic atmosphere from the lower latitudes—becomes either amplified or dampened as it wends its way through other elements of the Arctic system.

Box 3.1. What is an Extreme Event?

Extremes are in part a statistical notion. For example, extreme weather can, in principle, be defined as an event that is statistically rare, for example, a daily precipitation total exceeding the 95th or 99th percentile of the distribution of all daily events. One can define an extreme pattern of atmospheric circulation from the normalized (Z-score) index time series of an atmospheric teleconnection pattern such as the Arctic Oscillation or the Arctic Dipole Anomaly using daily, monthly, seasonal, or annual data. Extremes in the loss of sea ice extent, for the Arctic Ocean as a whole or for a given region, can be similarly defined on the basis of a statistical distribution, as can events like annual or peak river discharge. Because sufficiently long time series are often unavailable, defining extreme biological or ecological events can be more difficult and often remain subjective. For example, while massive starvation events of reindeer on the Yamal Peninsula observed in 2006 and 2013 (Forbes et al., 2016) can be viewed as extreme events simply in terms of the numbers of animals involved, this is not based on a formal statistical analysis. Yet, from the perspective of impacts to the social network reliant upon the reindeer, the episode was clearly catastrophic and extreme.

3.1. Extremes and Regime Shifts

Warming is fundamentally changing the dynamics of the Arctic, with far-reaching impacts on social systems, economics and human decision-making. At least in part, this warming is linked to regime shifts (i.e., large, long-lasting changes in the behavior, structure or function of atmospheric, oceanic, social and ecological systems). The *Arctic Resilience Report* (2016) (Carson and Peterson, 2016) has examined a number of regime shifts to understand their drivers and consequences, yet to date there is no synthesis of the ultimate impact of regime shifts, in part owing to the absence of systems-level research programs that explore extremes and their propagating effects. This incomplete understanding of the causes and consequences of extreme events precludes their prediction in a changing climate.

Superimposed on the overall warming trend affecting the Arctic are extremes such as in the poleward transport of atmospheric or oceanic heat energy, which then result in redistributions of water and constituents that exist in solid, liquid or gaseous phases. New system linkages may emerge, thus "re-wiring" the Arctic energy and water cycles. In terrestrial systems that experience warming, for example, increases in the frequency and intensity of rain events (especially, rain-on-snow or rain-on-ice) influence numerous elements of the Arctic system and can undermine their normal functioning. For instance, the survival of caribou and reindeer upon which Indigenous populations depend has been compromised by the lack of access to forage. The connectivity of individual subsystems (and currencies) means that the impacts of extremes will hardly remain uni-dimensional and local. The impacts can be broad, challenging the research community to make sense of them.

Addressing impacts is particularly challenging "downwind" of the original extreme event. While it is clear that the Arctic is seeing more positive temperature extremes and more negative extremes in sea ice extent, evidence for systematic changes in the extremes for other climate variables, such as precipitation, or for biological or ecological events is less comprehensive, although individual events can be well documented (e.g., Bazilchuk, 2013).

Potential intensification of the hydrologic cycle presents yet another challenge. Recent years have seen very deep cyclones form over the Arctic Ocean associated with extreme temperature events and with important impacts on sea ice cover. Has the number of extreme cyclone events actually increased? While evidence is accumulating to support that view (Sepp and Jaagus, 2011; Vavrus, 2013, Rinke et al., 2017; Day and Hodges, 2018), a definitive answer remains elusive. As the climate warms and increases the atmosphere's capacity to hold water vapor, one expects—as has been observed across the United States—more extreme precipitation events (NRC-COHS, 2011), as well as more rain-on-snow events such as those implicated in recent massive starvation events of caribous and reindeer. But whether any such changes have actually been realized remains unclear. An ongoing challenge is that for many variables, notably precipitation and its phase (solid or liquid), the observational network remains highly deficient (e.g., Rawlins et al., 2006). Many freezing rain events in the Arctic undoubtedly go unreported and even unobserved by humans.

What gives rise to extremes? For some events, there is certainly reason to suspect the origins to reside in the changing Arctic itself, yet it is also clear that many events manifest themselves in response to lower latitude drivers. For example, extreme precipitation events over Svalbard are clearly associated with "atmospheric rivers" that can be traced back to the tropics (Serreze et al., 2015). Similarly, events such as extremes in river discharge and flooding events in the Arctic have been clearly linked to weather anomalies (Rawlins et al., 2009a, 2009b) (**Box 3.2**).

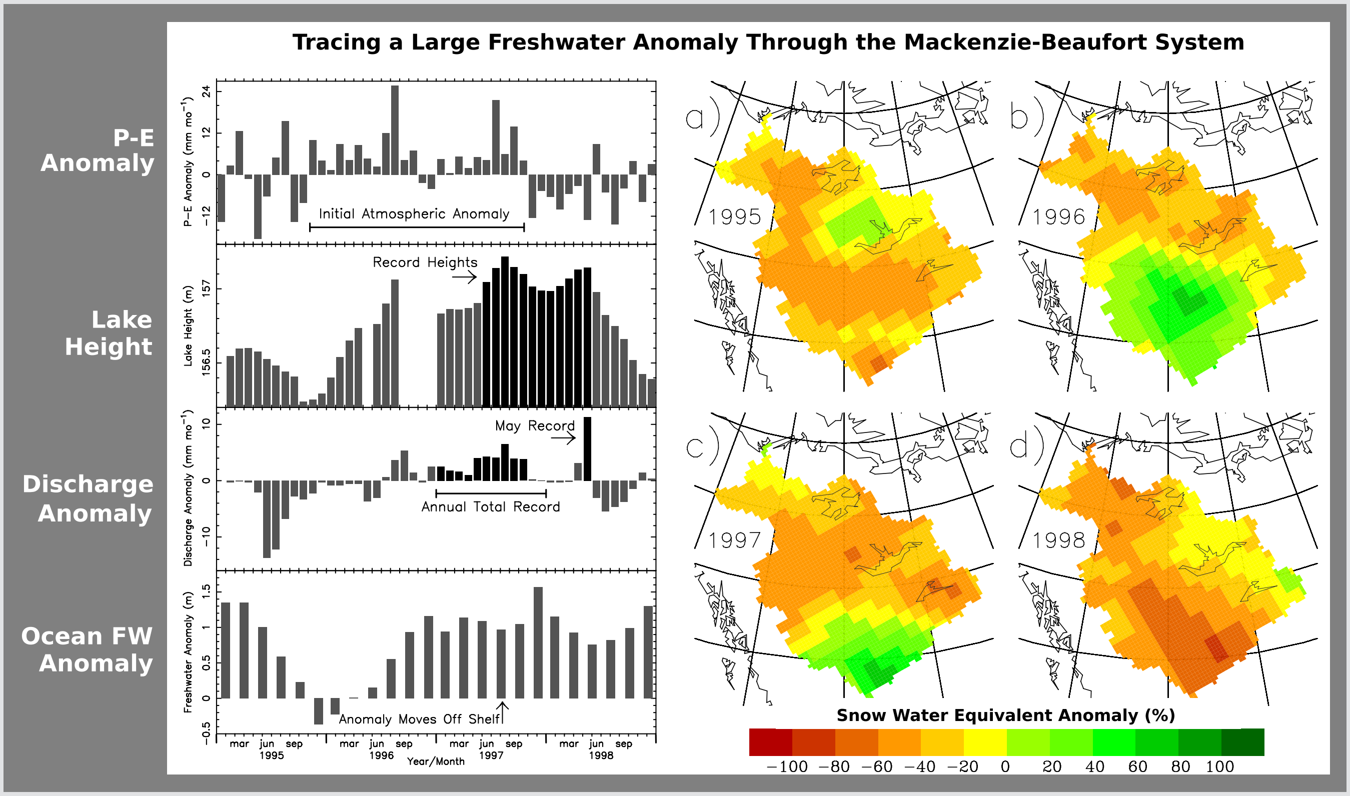
Analysis of extremes and their impacts is predicated on having sufficient observations, and this frequently presents a challenge. Thus, while it is true that surface air temperature is increasing (as an arguably less spatially and temporally heterogeneous signal of climate change), we are confronted by some essential questions: *Do we have sufficient data to accurately characterize its variability? Do we have sufficient skill in identifying the magnitude and timing of extremes and changes in rainfall and snowfall?* In the biological domain, there have been insights regarding general pressures on individual species to extremes, but population dynamics and cascading ecosystem consequences are yet to be fully elucidated. On land, local, single-season process studies on the impacts of changing snowpack (e.g., snow removal experiments), are available, but synthetic, system-level understanding has yet to take root. Sea ice dynamics and ocean ecosystems are another arena where extremes have been studied but for which our understanding remains incomplete.

In summary, while understanding of the Arctic system continues to improve, linkages between components with respect to the impacts of extremes have yet to be resolved. Because extreme events are rare by definition, integrated databases to identify their presence, sources and impacts are often lacking (see **Section 3.2**).

Box 3.2. Research Questions on Extreme Events Requiring a Currency-based, System-Wide Perspective

While care must be exercised to define appropriate baselines—which could include mean or changing trends—that extreme events are becoming more common in the Arctic is today less open to question than it has been in the past (Francis 2018). The strong connections between biogeophysical and social systems highlighted earlier in this report argue that an extreme occurring in one part of the Arctic system will generate follow-on impacts that would be difficult to trace and understand without adopting a systemic view. Many questions may come to mind regarding the precursors of an extreme event, its growth and evolution in the Arctic, which subsystems are impacted, their responsiveness to the stress, as well as their capacity to transfer, amplify or dampen impacts of the extreme. For example,

- Is there evidence for coordinated responses in the Arctic system to an extreme event, and if so, what are the dynamical linkages that produce this coordination, how does their strength vary through time, and to what degree do currencies define such responses?
- What are the positive and negative feedbacks that enable the system to succeed or to fail in re-establishing itself in response to exposure to an extreme event?
- Are there inherent space and timescales at which the key feedbacks operate that can guide research to better understand the Arctic system as a whole?
- Can we improve prediction of the occurrence of extreme events and are there ways in which human decisions can mitigate their adverse effects?



(left panel) Anomalies in net precipitation (P–E) across the Mackenzie River basin, height of Great Slave Lake, river discharge past the gauging station at the Arctic Red River, and ocean salinity (at 5 m depth) of the Mackenzie shelf and the Beaufort Gyre from 1995 to 1998. Large positive P–E anomaly in 1996 and 1997 (a manifestation of the energy currency) led to record lake heights and river discharge, which contributed 20% to the Beaufort Sea freshwater anomaly, but also was tempered by the presence of lakes available to temporarily store freshwater. (right) Anomalies in seasonal snow water equivalent in 1995, 1996, 1997, and 1998 (base period 1980–2001) averaged from simulations from five land surface models. Tracing the genesis and impact of these extremes involves understanding the dynamics of the atmosphere, land, and ocean—the core subdomains of the Arctic system. From Rawlins et al., (2009a); reprinted with permission, Taylor & Francis.

3.2. How Do Arctic Researchers Study Extremes?

Our understanding of extreme atmospheric events has arguably been best advanced through a more or less straightforward use of statistics. Improving Arctic observatories, targeted process studies, and dynamic modeling will yield greater understanding of changes in extreme events and their consequences across space and time.

The ability to define atmospheric extremes is fostered by both near real-time analysis and retrospective studies, greatly aided by advances in atmospheric reanalysis systems, such as the NOAA Climate Forecast System Reanalysis (CFSR). Reanalyses such as CFSR are run at higher resolution than their predecessors and use more advanced versions of data assimilation and numerical weather prediction models. With online daily analyses and forecast maps, like those provided by the Climate Reanalyzer (2018), it is now much easier to track the presence and evolution of extreme weather events. Convenient and time-saving data compositing and visualization tools for retrospective studies—developed for the first-generation NCEP/NCAR reanalysis (NOAA ESRL, 2018)—are now being developed for newer generation reanalyses (NOAA/ESRL, 2018), some of which now span a century or more (e.g., NOAA's 20CR, ECMWF's ERA-20C). By contrast, surface data available to examine extreme events (e.g., precipitation, temperature) tend to be scattered between multiple sites, reside in inconsistent formats, and can be difficult to acquire in near real time. Data downloads often involve painful experiences with clumsy web portals. Synthesis studies of extreme events transiting the Arctic's land, atmosphere, and ocean domains are most effective when a broad array of measurements and model outputs is employed.

System connectivity studies focused on extremes advanced in recent years. For example, impacts of atmospheric extremes on coupled ocean-atmosphere processes have been studied using daily maps of sea ice extent and concentration from passive microwave sensors in near real time from the DMSP series of satellites (NSIDC, 2018) and from AMSR-2 (Spreen et al., 2008). Progress in coupled modeling has enabled insights into how extreme weather such as the very strong August 2012 cyclone influenced sea ice conditions (Zhang et al., 2013), and how unusual atmospheric conditions in 2007 led to record high Eurasian river discharge, while at the same time contributing to a then-record-low September sea ice extent (Rawlins et al., 2009b). Data from satellite remote sensing, atmospheric reanalysis and field studies have been combined to understand how autumn rain-on-snow events and an unstable snowpack (which are likely to become more common in a warmer future climate) make it difficult for reindeer to forage, causing widespread starvation (**Box 3.3**). It has been argued that the ecological and socioeconomic impacts from the catastrophic 2013 event will not completely unfold for years to come, and the proposed link between climate regime shifts, sea ice loss, more frequent and intense rain-on-snow events and high reindeer mortality will have serious implications for the future of tundra nomadism (Forbes et al., 2016).

While models play an important role in developing and testing our understanding of system-level extremes, they must be calibrated and tested based on observations (**Section 1.3, Box 1.4**). Field observations from individual locales are clearly valuable, even in broader-scale studies. Because the nature of extremes explicitly involves both spatial and temporal factors, models also require more general or synoptic-scale field observations and monitoring network data. This points to the necessity of tiered monitoring networks comprising remote sensing, meteorological stations, synoptic measurements, and long-term experiments (e.g., LTER) from the highly localized to the Pan-Arctic (see also **Section 4.8**).

3.3. The Role of System Pre-Conditioning

If a system reaches a critical threshold, an additional "nudge," such as from natural climate variability, may set in motion a chain of events that originates in one part of the system but then moves into others, collectively transforming the system to a new state. Alternatively, the system might rapidly confront and respond to a "gathering storm" of related, simultaneous events across several Arctic domains (e.g., the atmosphere, chemistry, biology and human elements). The system could exhibit adaptive capacity to resist change, allowing the system to "bounce back," a phenomenon sometimes referred to as resilience. Understanding how the Arctic system previously reacted to a particular set of forcings versus how it is likely to respond today under the same forcings but with a new background state constitutes an important research challenge.

The melting point of water is an obvious environmental threshold. In the Arctic Ocean, this threshold is central to the sea ice-albedo feedback introduced in **Chapter 2**. Better understanding the sea ice-albedo feedback is critical in its own right, but from a systems viewpoint it is an important means by which the Arctic generates interactions with the lower latitudes (**Box 3.4**), and whether those interactions represent the cause or the impact of climate anomalies in the lower latitudes. Because today's ice cover at the beginning of the melt season is thinner than it used to be, it takes less energy to melt out the sea ice in summer. Such thinning represents a pre-conditioning that has altered the response of the ice cover to natural variability. For example, the very low September ice extent of 2007—tied for second lowest in the satellite record as of this writing—was clearly a response to a summer atmospheric circulation pattern favoring summer ice loss. But it is likely that had the same pattern set up 30 years previously, when the ice was thicker and more resilient, the response would have been much less pronounced. Much can be learned by probing the most exceptional of extreme events, like the unprecedented winter warmth noted in 2016 (**Box 3.5**), which provides a window into how the atmospheric-ocean-ice system interacts and produces a host of preconditioning processes that affect both the Arctic as well as the lower latitudes.

A number of studies (Ogi and Wallace, 2007) have shown that summers in which there are many cyclones over the central Arctic Ocean generally tend to end up with a higher September sea ice extent. This is because summers with

Box 3.3. The Unreliable Snowpack

The Arctic has experienced greater warming in recent decades than the rest of the globe. An unreliable snowpack is the product of several linked Arctic system processes. For some time now, researchers have been accumulating evidence that higher temperatures have led to higher rates of precipitation generally and rainfall in particular (e.g. IPCC 1996, Hansen-Bauer and Førland 1998, Deep Cole 2018). Atmospheric warming is causing a greater fraction of snowfall to melt before it reaches the surface, and is thus associated with losses in snowfall and snow cover, with implications for the region's flora and fauna. Heavy snow and ice loading on trees creates direct damage, weakened defense against insect attack, and altered forest species composition. More frequent, widespread, and severe episodes of freezing rain events lead to ice armoring of ground vegetation, obstructed access to winter forage by reindeer and caribous, and an unsuitable environment for subnivian rodents.

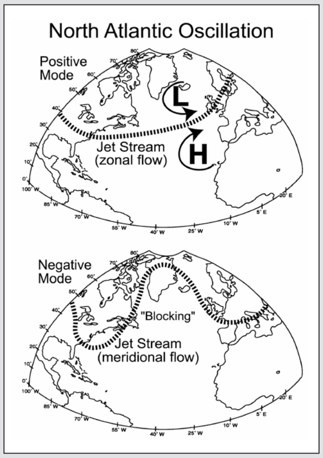
Part of the surface warming arises through the advection of heat from the mid-latitudes, while some is locally sourced; sea ice loss is known to be an important driver. Increased precipitation alters the fate of water entering the land surface, redistributing the way that it is partitioned into evapotranspiration, surface and subsurface runoff, and storage. Higher rainfall, warmer soils and faster snowmelt can also create ice wedge degradation and flooding associated with aufeis (layered-ice produced by groundwater during freezing temperatures that subsequently can block river channels). At the same time, increased aufeis can occur in warm years in the coldest part of the Arctic, yet those warm years with heavy snowfalls show reduced aufeis in the northernmost boreal zone. Higher flows of freshwater runoff can also affect sea ice concentrations in coastal areas. In the Arctic Ocean, warming has led to thinner ice, which may favor increased early season snowfall through enhanced evaporation (Callaghan et al. 2011).

There are several "downstream" effects of these systemic physical changes. Rapid runoff and subsequent flooding may jeopardize infrastructure: damaging roads and bridges and increasing the likelihood of power outages. Rain-on-snow events with subsequent re-freezing can make it difficult if not impossible for herbivores to forage. Later sea ice freeze-up and delayed snow accumulation on ice prematurely exposes ringed seal pups to predation and exposure, affecting polar bear and human populations. Changing seasonal patterns of rain and snow combined with warming will continue to affect sea-ice melt, infrastructure, wildfires, insect disturbances, vegetation structure and function, wildlife habitat, and people.

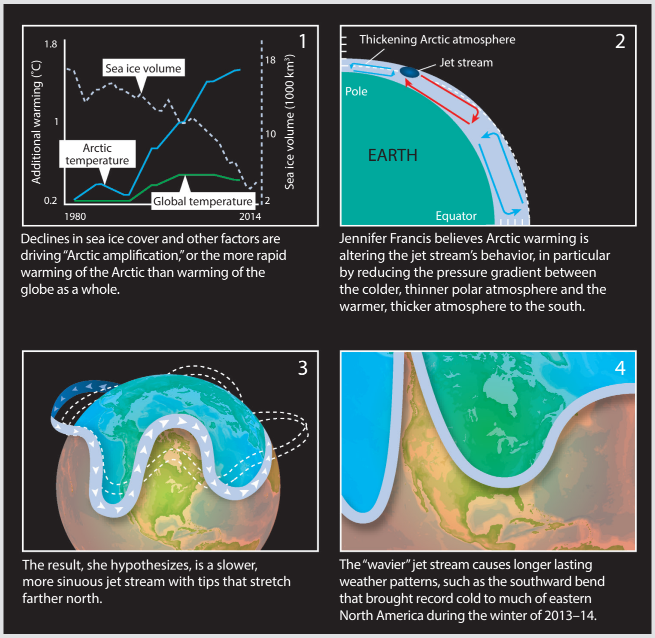
Box 3.4. Extreme Weather: Arctic Teleconnections to the Lower Latitudes

The polar vortex, which gained public notoriety during recent wintertime cold air outbreaks in middle latitudes, is a good example of a systems-level phenomenon involving extremes. By probing this concept, scientists are assembling an answer to the question: *Are there links between amplified Arctic warming and severe weather during mid-latitude winter?*

At mid-atmospheric levels (roughly the altitude at which jet airliners fly) the boundary between cold Arctic and warmer air to the south is delineated by a fairly narrow ribbon of strong winds known as the polar front jet stream (Waugh et al., 2017) that blows broadly from west to east. The jet stream is a meridionally wavy feature, and the formation of surface weather disturbances (cyclones and anticyclones) is favored along particular locations in these waves and the jet stream guides their motion. If the pattern of waviness changes, so will the distribution and intensity of surface weather disturbances (Cohen et al., 2007; Furtado et al., 2015).



Temperature variations lead to changes in the polar front jet stream, which in turn lead to changes in the distribution of sea level pressure and surface weather conditions. While these dynamics have been widely studied, links to Arctic warming are not fully understood (e.g., Francis and Vavrus, 2015; Francis, 2017). Image from Bradbury et al. (2002), reprinted with permission, Wiley.



Declines in sea ice cover and other factors are driving "Arctic amplification," or the more rapid warming of the Arctic than warming of the globe as a whole.

Jennifer Francis believes Arctic warming is altering the jet stream's behavior, in particular by reducing the pressure gradient between the colder, thinner polar atmosphere and the warmer, thicker atmosphere to the south.

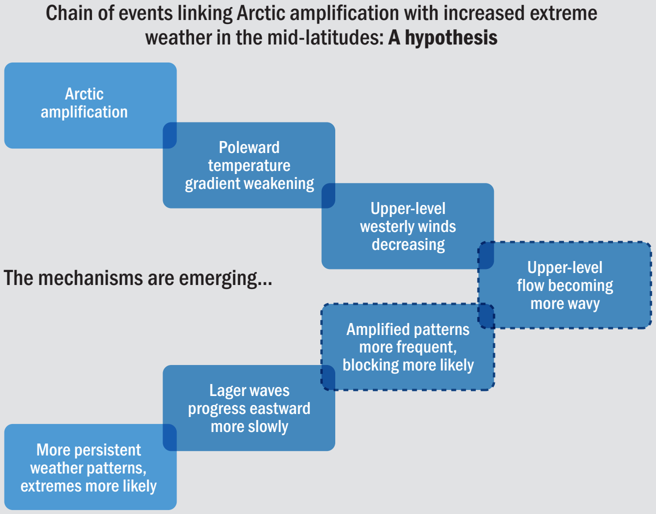
The result, she hypothesizes, is a slower, more sinuous jet stream with tips that stretch farther north.

The "wavier" jet stream causes longer lasting weather patterns, such as the southward bend that brought record cold to much of eastern North America during the winter of 2013–14.

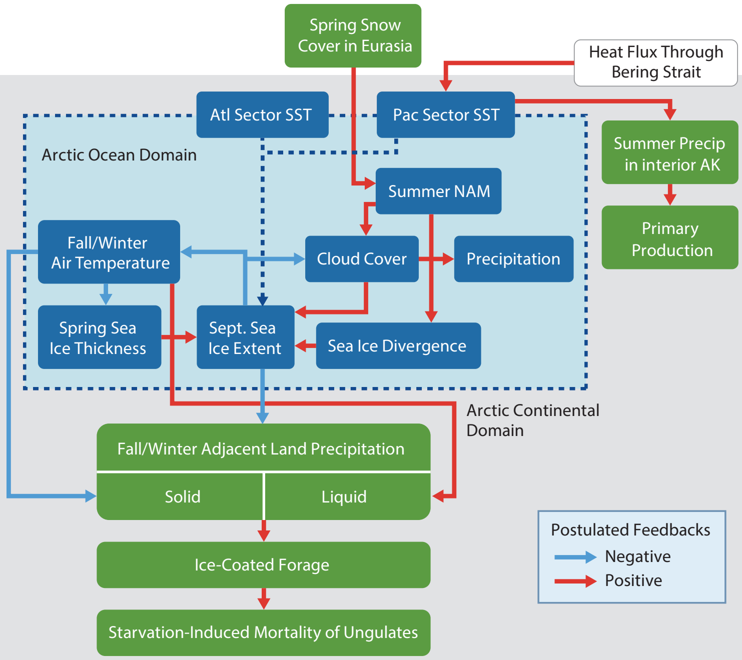
Summary of links between Arctic amplification and persistent weather across the lower-latitudes. From Kintisch (2014), reprinted with permission, AAAS.

During autumn, the vertical propagation of either wave energy or wave drag can accelerate or decelerate the flow at higher atmospheric levels within what is known as the stratospheric polar vortex (PV). These influences can persist into the following winter (Plumb, 1989; Manzini et al., 2018). There is strong evidence that interactions with diminished sea ice in the Barents-Kara Seas and/or extensive Eurasian snow cover during autumn may weaken the PV (Cohen et al., 2014). This surface forcing appears to promote a dip in the polar front jet stream over East Asia along with a northward excursion of the jet stream near the Ural Mountains (Zhang et al., 2016). This then favors strong vertical propagation of wave energy from the troposphere into the stratosphere (Cohen et al., 2014; Kretchmer et al., 2018).

Enhanced upward wave propagation tends to disrupt the PV, which creates circulation anomalies that can disrupt the stratosphere and subsequently propagate downward toward the surface in winter. This creates a "memory mechanism" that prolongs the initial influences of sea ice loss and expansive snow cover. Surface temperatures over the Arctic tend to increase, and the wavier jet transports mild air northward, further warming the Arctic. Over mid-latitude continents, meanwhile, increased southward penetration of cold Arctic air favors persistent cold spells along with a greater likelihood of snowstorms in the mid-latitudes.



Summary of links between Arctic amplification and persistent weather across the lower-latitudes. Modified from Francis (2014).

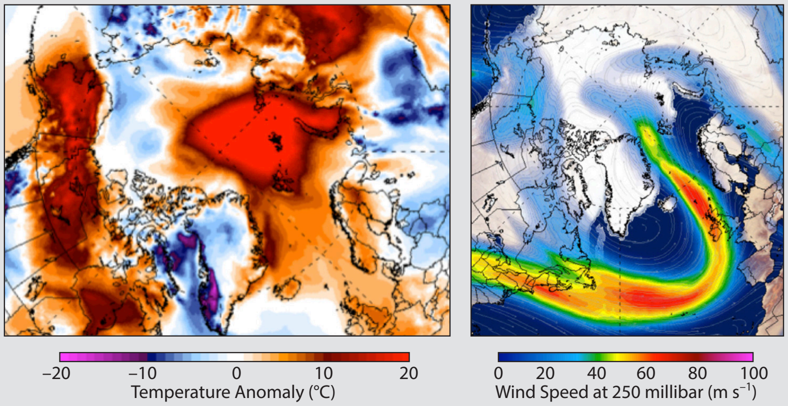


Box 3.5. Unprecedented Winter Warmth and Year 2016

Recent winters have seen unprecedented heat waves over the Arctic Ocean. At the very end of December 2015, there was a brief period when the surface air temperature at the North Pole neared or reached the melting point. This extreme warmth was associated with a contorted jet stream that drew heat and moisture far into the Atlantic side of the Arctic Ocean, a convergence known as an atmospheric river. As the jet stream and water vapor plume passed over England, it brought intense rainfall and flooding to that area. Unusually warm conditions persisted through much of the winter of 2015–2016. The seasonal maximum ice extent recorded on March 24, 2016, was the lowest ever measured by satellite observations, besting the previous record set only a year earlier (Francis, 2018), and the maximum extent the following March nearly set another record. After the seasonal sea ice minimum of 2016 on September 10, the second lowest on record, the sea ice started its annual pattern of growth, but then the excessive warmth returned. A persistent atmospheric pattern set up with the jet stream over the northern North Atlantic oriented almost due north/south, directing a series of strong storms deep into the Arctic Ocean, each one associated with extreme positive temperature anomalies. Both October and November 2016 saw record lows in sea ice extent, December 2016 being the second lowest. March 2017 sea ice maximum ended up setting another record low.

What was the cause of these Arctic Ocean heat waves and how do they link with sea ice conditions? The wiring diagram presented above summarizes a hypothesis. Evidence has emerged that low sea ice extent in the Barents Sea promotes strong heating of the overlying atmosphere, which then favors persistence of the unusual winter jet stream pattern. *But why the low ice extent in this region?* At least in part, it manifests a shift in the cold halocline leading to a stronger influence of warm Atlantic-derived waters that inhibit ice formation. But the heatwaves associated with each storm passage also appear to have limited ice growth. It has also been argued that the unusual jet stream pattern has a remote cause, such as sea surface temperature anomalies in the tropical Pacific (Lee 2014). Another possibility is that the climatological ridge located in the region near the Ural Mountains can access the additional heat sources provided by Barents Sea ice loss, thereby intensifying the ridge and favoring increased persistence (Cohen et al., 2014; Kretchmer et al., 2018).

Recent unusual weather patterns have not been limited to autumn and winter, as the summer of 2016 was remarkably stormy over the central Arctic Ocean. Cyclone after cyclone moved into the central Arctic Ocean, including a pair of tremendously deep low pressure systems in August. Strong low pressure systems have a tendency to chew up the ice cover, spread the ice out to cover a larger area, and bring cloudy and relatively cool conditions, inhibiting melt—but the predictability of sea ice cover in response remains challenging (Petty et al., 2018). Without this stormy summer pattern, September sea ice extent for 2016 may well have reached a new record low—a prime example of the importance of pre-conditioning combined with short-term weather variability.



Temperatures above the freezing point recorded near the North Pole on December 30, 2015, associated with a contorted jet stream drawing heat and moisture far into the Arctic Ocean. As the jet stream and atmospheric river passed over England, it brought intense rainfall and flooding. (left) From Saha et al. (2014) (data) and Climate Reanalyzer (2018) Photo credit: Robert McSweeny, Carbon Brief, https://www.carbonbrief.org/analysis-how-december-2015-topped-chart-as-uks-wettest-month-on-record cyclonic conditions tend to be relatively cool (with summer precipitation often falling as snow), and wind patterns tend to force a divergent circulation of the ice motion, spreading out the ice to cover larger areas. However, this relationship may be changing. Individual strong storms, such as the event observed in August of 2012, appear able to force reductions in ice extent, such as through the mixing of warm water upwards (Zhang et al., 2013). This may relate to observations showing that in response to a decrease in ice concentration and thickness, the ice cover has become more mobile (Olason and Notz, 2014).

Concerns have been raised that there may be some critical threshold in sea ice thickness or greenhouse gas concentration that—once reached—will initiate a rapid slide toward a seasonally ice-free Arctic Ocean. However, recent work argues against this extreme scenario. This is because winter heat loss acts as a negative feedback; if September extent is especially low, there will be an especially large heat loss from the ocean, cooling the ocean quickly and promoting sea ice formation. Modeling studies (Tietche et al., 2011) provide evidence to support to this contention. Because of the negative feedback, years with a September extent well below the trend line are almost invariably followed by higher extent the following September (Serreze et al., 2016; Serreze and Meier, 2018). It seems increasingly likely that the slide toward a seasonally ice free Arctic Ocean will continue along the observed trajectory—a strong and perhaps accelerating downward trend with pronounced interannual variability. Additional processes also can create negative feedbacks or dampening within the system, as with the example of anticipated increased cloudiness associated with Arctic amplification that would additionally dampen the sea ice-albedo effect, though it is likely that positive feedbacks dominate (Pithan and Mauritsen, 2014). Disappearing sea ice means that increasing wind fetch can enhance sea spray and primary production, with resulting increases in aerosols/cloud condensation nuclei, including from biogenic sources produced by phytoplankton (Woodhouse et al., 2013), thus modifying the propensity of the arctic climate system to generate precipitation.

In the biological domain, the loss of refugia for life forms—polar bears being a prime example—relates to the loss of ice at particular times of year and may lead to a change in genetic diversity when the species in question is unable to keep pace with rapid changes in its habitat. By contrast, in an ice-diminished Arctic, there may be a change from a benthic to a pelagically dominated ecosystem. Over land, a temporary greening of tundra landscapes has been recorded, but the reverse has also been recently observed (Epstein et al., 2016), and the cause of this abrupt change in direction is unclear, raising the question: *Is the system resilient to change or will the greening trend dominate in the longer term?* Warming can also invoke at least a temporary wetting of thermokarst lakes, but later drainage and increased susceptibility to drying makes land-based ecosystems ultimately more susceptible to drought and fires.

3.4. Societal Implications of Extremes

Extremes present obvious challenges for transport, resource provisioning, and infrastructure. Policymakers and practitioners will increasingly look to the science community to help identify options to and manage risk. Policy-driven demands for information reside outside the comfort zone for many researchers, while the evolving research agenda must ultimately confront a long list of potentially costly societal issues linked to extremes (see **Section 1.2**). Broadly, these will include the tandem issues of climate adaptation and mitigation, and will require workable strategies to ensure sustainable industrial and community development.

While a warmer Arctic poses challenges to its residents that rely on snow cover and sea ice for transportation and traditional practices, an ice-diminished Arctic Ocean is expected to attract more commercial shipping, extraction activities (especially for oil and natural gas) and tourism. Some of these activities are already happening. Although the downward trend in summer ice extent obviously makes the Arctic more accessible, sea ice conditions will remain highly variable for decades to come. The thinner, less compact ice will also be more mobile, and hence more responsive to changes in surface winds. Therefore, trans-Arctic marine shipping is, on the one hand, an opportunity associated with the loss of sea ice, but it is also a challenge that embodies weather extremes such as fog and increased storminess, exacerbated by incomplete bathymetric data and capricious sea ice behavior. All of these phenomena conspire to increase risks to business and livelihoods. On land, harvesting newly accessible Arctic renewable and non-renewable energy resources will be challenged by the compromised integrity of ice roads used to access extraction sites, as for oil and gas. Such issues go far beyond traditional academic circles and into the domain of business risk assessment. This emphasizes the need for research leading to improved weather, climate and environmental forecasting over subseasonal-to-seasonal time horizons.

There is considerable uncertainty about how extreme events translate into growing vulnerabilities. An obvious example is the increasing damage observed in seaside communities from coastal erosion (e.g., Overeem et al., 2011). Several related processes are at work. With less summer sea ice, storms now have a longer fetch over open water, leading to larger and more damaging waves. In areas experiencing erosion, the landscape is largely composed of sediments held together by permafrost, but with air and ocean waters now warmer, permafrost has warmed and thawed. Thus both mechanical and thermal erosion are contributing to the loss of shoreline stability and the product of an interplay of the Arctic's climate, meteorological, geomorphological, and oceanic systems.

Non-climate related events also play out in unique ways in the Arctic. A massive oil spill in Arctic waters would qualify as an extreme event, and in fact would face a whole system of obstacles to minimize its impact. For instance, technologies and infrastructure to clean up a large spill in remote, icy waters are in their infancy, and they face huge biochemical limitations to decomposition because of low temperatures. Added to those obstacles is the fact that there are no ports-of-call (at least none in the United States) from which to base response and rehabilitation efforts (USARC, 2012). In the summer of 2016, the cruise liner *Crystal Serenity* transited the Northwest Passage via Amundsen's route, becoming the largest cruise ship ever to traverse the historically forbidden ice-bound territory. With the assumption of more transits of this type, the possibility of accidents rises: grounding, encounters with ice, even sinking. But the infrastructure to deal with such an extreme event is, practically speaking, non-existent. Evaluating the impacts of such events on ocean pollution, Indigenous fisheries or biodiversity require an additional layer of understanding with respect to the system's basic characteristics.

Surface melt extent and intensity over the Greenland ice sheet has generally increased, but is highly variable from year to year. In 2012, nearly the entire ice sheet saw at least some surface melt, and melt rates were intense at lower elevations. This was associated with an anomalous ridge of warm air that resulted in a stagnant weather pattern that brought very warm conditions over the ice sheet (Ngiem et al., 2012). The event caused extreme flooding of the Watson River near the village of Kangerlussuaq, which hosts one of the island's busiest commercial airports. While this extreme event was clearly driven by short-term meteorology, weather patterns that favor heat waves are likely to become more common as the Arctic continues to warm (Hanna et al., 2016), further accelerating the contribution of meltwater from land ice to rising sea levels.

3.5. Policy Responses Aimed at Managing the Arctic System

Recognition that societally critical impacts exist beyond the biogeophysical changes taking place in the Arctic motivates broad-scale and even internationally coordinated decisions. Scenario-building and visions for a 21st century Arctic will, of necessity, reflect system-level perspectives, insofar as a human decision in one domain can easily reverberate throughout the Arctic's linked atmospheric, terrestrial, and oceanic components, and will bear legacies for decades if not centuries to come. (A further discussion of how scenarios are formulated, with an exploration of the value of reduced complexity models, is offered in **Chapter 4**.) The Arctic may serve as an important testbed with regard to evaluating the effectiveness of environmental management strategies such as carbon emission controls or strategic land management for ecosystem-based carbon sequestration. Such interventions must be designed around systems-level knowledge and verified by observations (see **Chapter 5**).

The Arctic is likely to remain attractive to the global investment community, but sustained economic development requires an analysis of both the risks and opportunities of financial investments. These necessarily will include systems-oriented information on the biogeophysics of the system, cold-region engineering assessments, resource inventories, and risk profiles as used in the insurance industry (Vörösmarty et al., 2015). Investments requiring such knowledge include enhanced trans-Arctic shipping along with the requisite monitoring of dangerous weather extremes and baseline studies of distributions and dynamics of ice conditions impeding safe navigation. Another example is the economic viability of resource extraction that requires an understanding of the long-term vulnerability and resilience of land and ocean-based ecosystems. The requirement for sound knowledge is amplified in the context of rapidly shifting conditions in the Arctic environment that need to be understood and accommodated to support complex logistical operations.

CHAPTER 4. APPROACHES TO SYNTHESIS

To rank-and-file scientists, policymakers, and increasingly the public (Hamilton et al, 2014), the notion that the Arctic is rapidly changing is a fact. Through this report, we have presented a growing body of evidence to support the conclusion that all the main elements of the Arctic system are shifting—its weather and climate, its ocean sea ice and circulation dynamics, hydrology and permafrost, and biology on both land and ocean. Recent literature underscores the fact that these changes are coordinated and systematic, with some—notably sea ice—occurring much more rapidly than many state-of-the-art models today can predict (Meier et al., 2014).

The challenge is to develop technical approaches and research infrastructure that outpace the very changes researchers seek to study. From a systems standpoint, this requires toolkits and data sets that can be used to interpret, understand, and forecast Arctic change as its evolves, reverberates through the Arctic system, and then affects other parts of the Earth system. The urgent need comes down to this: A collaborative exploration of unprecedented sophistication to discover how the system is "wired" together. Once secured, these capabilities then enable response strategies to be formulated to help prepare for, cope with, and potentially reverse negative impacts—such as permafrost loss leading to infrastructure damage—by also seizing upon opportunities to enhance the safety and success of new commercial enterprises.

In some sense, the Arctic science community has already responded to the need to consider at least the major interconnections, and indeed it has developed skill at synthesizing some complex, interdisciplinary research challenges through a series of existing programs, including those funded through the National Science Foundation (**Box 4.1**). Building on this legacy, this chapter summarizes some of the key design considerations for a new strategy aimed at Arctic synthesis and system-level research, recognizing that there are several important "Arctic realities" that need to be appreciated and accommodated by such an initiative. It next describes the necessity of focusing the community on specific systems-level targets to avoid fragmentation of research focus and effort. The chapter then elaborates on the need for a productive interplay between observations and modeling, revisiting notions of inductive and deductive thinking presented in **Chapter 1**. It concludes with a review of important sentinel products of synthesis: fundamental benchmarks, heuristic studies, and models of varying sophistication.

4.1. Design Considerations

There are four essential realities that must be confronted in the process of designing and executing strategies for new synthesis and systems-level research in the Arctic. In the broadest terms, they are:

Reality #1: Processes in the Arctic are complex, cascading, and nonlinear. They are also highly interdependent, embody the biogeophysical and social science disciplines, and cross strikingly different boundaries depending on the perspectives of the research or applications in question (**Figure 4.1**). This provides challenges to Arctic researchers in terms of assembling and harmonizing the observational underpinnings of systems-level analysis, from which contemporary benchmarks and future tracking systems can be formulated. In addition, process-level understanding in one domain may be at a higher level of sophistication than another. For instance, exploring freshwater interactions with sea ice and ocean circulation may be more advanced than the understanding of ocean ecosystem dynamics, but they still ultimately have to be harmonized in order to "trade" the currencies of their interaction. Rapid developments in cyber-infrastructure are enabling new research on complex Arctic systems, using either Earth system models or data assimilation models (e.g., Clement Kinney and Maslowski, 2012; NOAA ESRL, 2018), which are essentially counterparts to numerical weather forecast models but in the Arctic Ocean domain.

Box 4.1. A Brief History of NSF and Other Agency Support for Synthesis Research

It is important to note that calls for system-level understanding and synthesis did not begin with this report and that a long history of NSF-funded programs will contribute to the design of a next-generation effort. In 1989 the NSF Office of Polar Programs (OPP) initiated the Arctic System Science (ARCSS) program, with its stated goals to (1) understand the physical, chemical, biological, and social processes of the Arctic system that interact with the total Earth system and thus contribute to or are influenced by global change, and (2) advance the scientific basis for predicting environmental change on a decade to centuries timescale and for formulating policy options in response to the anticipated impacts on humans and societal support systems. Initial ARCSS projects were focused on subdomains of the larger system and included Land Atmosphere Ice Interactions (LAII) and Ocean Ice Atmosphere Interactions (OAII) followed by Paleo-environmental Arctic Studies (PARCS), Human Dimensions of the Arctic System (HARC), Community-wide Hydrologic Analysis and Modeling Program (CHAMP, later called the FreshWater Integration [FWI] project), Pan-Arctic Cycles, Transitions and Sustainability (PACTS), and Changing Seasonality in the Arctic System (CSAS). ARCSS also funded large field efforts such as the 1997-98 Surface Heat Budget of the Arctic Ocean (SHEBA) experiment in the Beaufort Sea. These subsystem studies provided essential process-level understanding as well as calibration and validation data upon which subsequent systems modeling studies were based.

The Arctic research, education, and policy communities have also been catalyzing new perspectives aimed at systems-level questions, including ARCSS-funded synthesis activities such as the Big Sky workshop (Overpeck et al., 2005), planning within the ARCSS Committee and a consensus dialogue begun in 2005 by more than 100 Arctic natural and social scientists, technologists, educators, policy and outreach experts (ARCUS, 2007a, 2007b, 2014a). ARCSS Synthesis, Integration and Modeling Studies (SIMS), Organization of Projects on Environmental Research in the Arctic (OPERA), and Synthesis of Arctic System Science (SASS) were programs designed to support Arctic systems-level thinking and synthesis. While system-level understanding has been a long-term and stated goal of ARCSS, and while great strides have been made through the years in understanding system components and connections, a true systems-level view of the Arctic has remained elusive (Swanberg and Homes, 2013).

By their very nature, SEARCH (Study of Environmental Arctic Change) and an international counterpart, ISAC (International Study of Arctic Change) (Murray et al., 2010; ARCUS, 2014b) are motivated by systems-level research themes and integrated modeling and observational approaches. SEARCH, founded in the early 2000s, is a collaboration among researchers and stakeholders to study the rapidly changing Arctic and synthesize that understanding into a broader characterization of the Arctic system and its role in the global climate system (from https://www.searcharcticscience.org). SEARCH was established to help society observe, understand, and respond to the rapidly changing Arctic. SEARCH addresses the important processes, drivers, and implications of shrinking land ice, diminishing sea ice, and degrading permafrost and characterizing the role these processes play in global systems. SEARCH's interdisciplinary action teams strive to develop the understanding and evidence needed to inform agencies, policy- and decision-makers, and Arctic residents. The primary goals are to:

- Improve understanding, advance prediction, and explore consequences of changing Arctic sea ice;
- Document and understand how degradation of near-surface permafrost will affect Arctic and global systems;
- Improve predictions of future land-ice loss and impacts on sea level; and
- Enhance science communication among Arctic natural and social scientists, scientists from other communities, local Arctic stakeholders, journalists, and the public.

Beyond NSF, the Interagency Arctic Research Policy Committee (IARPC)—comprising 14 agencies, departments, and offices of the federal government—helps to coordinate a broad research agenda in many domains that are inherently systemic in nature. Its current collection of nine research foci comprise: health and well-being, atmosphere, sea ice, marine ecosystems, glaciers and sea level, permafrost, terrestrial systems, coastal resilience, and environmental surveillance. Governmental activities beyond pure research also catalyze systems research and synthesis. A case in point is the deputy-level Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska (Clement et al., 2013), convened in 2011 as part of a deliberative process to consider the scientific needs of a structured decision-making process (Holland-Bartels and Pierce, 2011) for offshore drilling across the northern Bering Sea, and Chukchi and Beaufort Seas in the ocean domain and the North Slope of Alaska on land. It is apparent that the scientific needs associated with the permitting process necessarily span a wide swath of scientific disciplines (biogeophysical, social, economic, cultural), specific topics, time spans and time horizons (literally from minutes to decades to century), and methodologies (from field studies to census and survey approaches to advanced simulation). Many of the variables, indicators, and metrics associated with the offshore permitting process could be delivered to regulatory agencies by the research community. However, this requires systems-level thinking and synthesis across the disciplines, a requirement that has proven in practice difficult to achieve across the research spectrum. While the assertions contained in this report apply to basic Arctic systems science, they have also been identified in the context of the permitting process. To quote USGS circular 1370 (Holland-Bartels and Pierce, 2011): "Yet, in many ways, relatively little is known about the Arctic in large part because many of the studies are targeted in focus and independently conducted with limited synthesis, even within studies on the same topics…" Arguably, systems-level understanding and synthesis must be intrinsic to the enterprise at hand from the beginning and not simply as an add-on to avoid the status quo.

Reality #2: Arctic domain data streams are proliferating. Information resources derived from observatories (e.g., from AON, SAON, CEON and others) are proving themselves to be increasingly valuable to the research community, but at the same time they are complex and typically unharmonized, as they are generated by a wide array of sources and independent purposes (biogeophysical and social system models, data assimilation schemes, observational networks, in situ experiments, remote sensing and GIS) (Figure 1.5). These data provide a critical foundation for observation-based understanding of full-system behaviors and are also needed in model calibration and validation, yet they still need the step of harmonization and integration to make them more user-friendly to the modeling community. In situ experimental work (e.g., at LTER sites) is critically important in understanding key processes and long-term changes. However, they may fail to yield parameters and validation targets that are of use in bigger-picture, full-systems assessments, which necessarily include heterogeneous subsystems that may not have been adequately sampled in the field. Some large-scale field experiments employ scaling strategies (e.g., as part of NASA-ABoVE) to compensate for this deficiency.

Reality #3: Disciplinary divides remain an obstacle. Different disciplines have different approaches to process studies and data management, and typically work with contrasting domains, nomenclature, and definitions with respect to spatial and temporal scales (Figures 4.1 and 4.2). ”Microscale” to a microbial ecologist, for example, is vastly different from the definition guiding a sea ice dynamicist.

Reality #4: Policy-driven research. The “hot” issues of today are of more than simple academic interest, and knowledge demands (that ultimately result in research topics) are being defined by national and international Arctic policy, decision-making and management concerns. This means that curiosity-based science may need to share the forefront of research with societally defined and economically relevant questions, which in the end may be pragmatic but also require new types of systems-level thinking. One intrinsically systemic example is how to balance the costs and benefits of a major expansion of timber operations in boreal forest regions. Such development would ultimately yield economic benefits at local, regional, and national scales, but it might also result in potential losses (or sequestration) of CO_2, changes in albedo, or other climate-land feedbacks that may cause further regional and global warming.

4.2. Establishing Focal Points and Clear Targets for New Research

The large and growing number of Arctic science programs and projects (Box 4.1) is a testament to the capacity of the Arctic research establishment to execute cutting edge research. However, the typical disciplinary nature of these projects, and the general lack of unified systems-level projects (Swanberg and Holmes, 2013), misses an opportunity to exercise the products of this research in a way that builds a synthetic view of the Arctic.

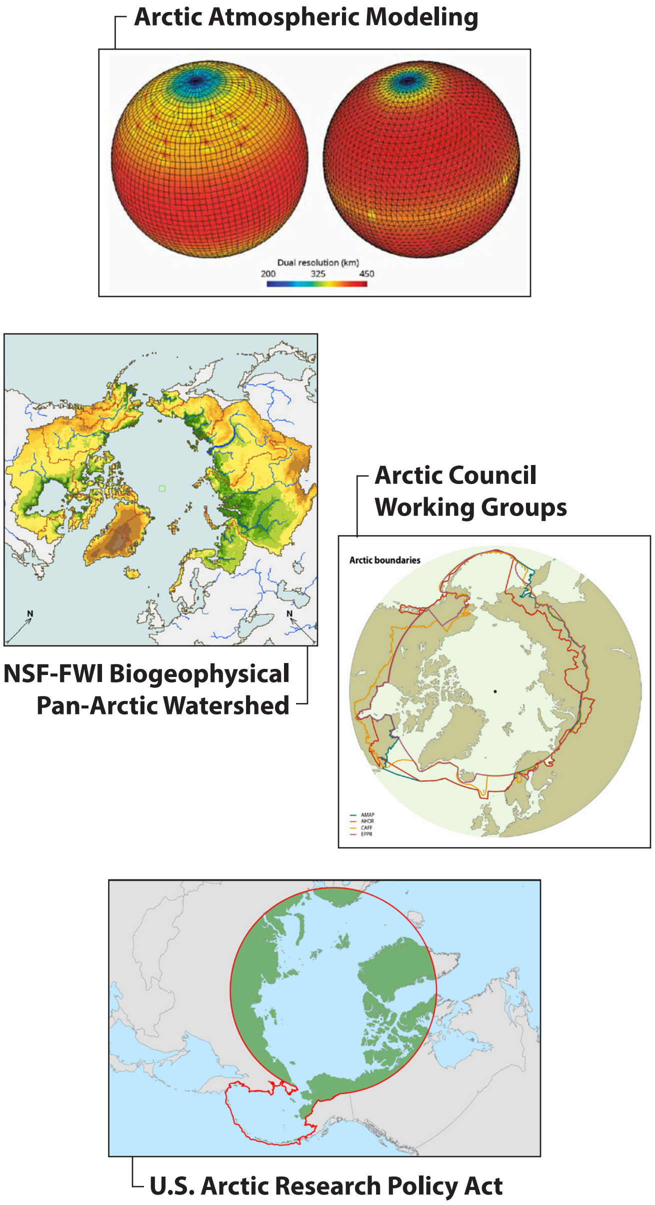


FIGURE 4.1. Boundaries as defined by two biogeophysical perspectives and two policy-related initiatives. Arguing that the Arctic is a pivotal part of the Earth system means that the full global system constitutes another Arctic-relevant boundary. Top panel from Smolarkiewicz et al. (2015).

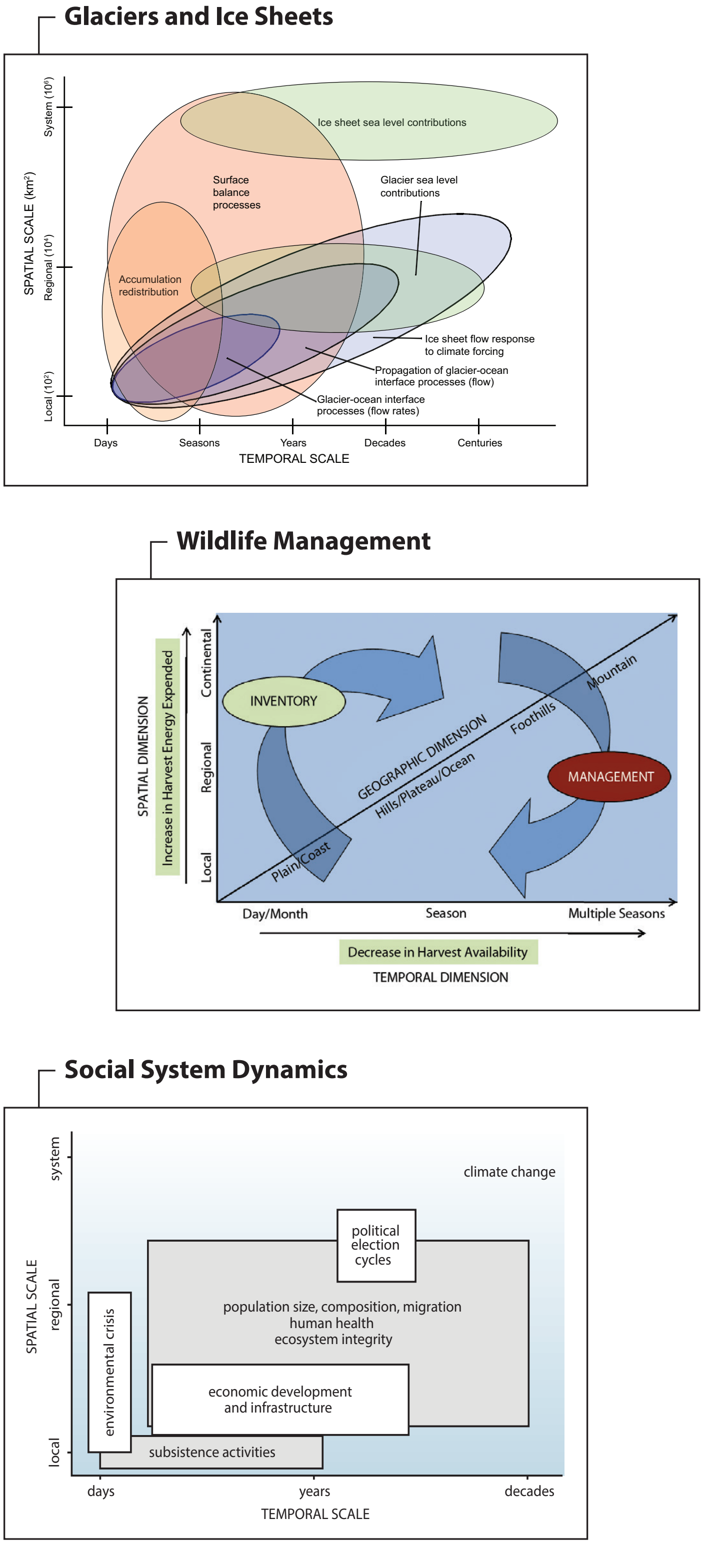


FIGURE 4.2. The panels above represent strikingly different concepts of space and time in three research domains and disciplinary communities. Insofar as system synthesis will require cooperation across several disciplines, such differences have a very practical impact on how such synthesis will be executed, and argues for common strategies and frameworks to break down the perpetuation of these divisions. Some approaches are defined in this chapter. From USARC (2010).

In this context, challenge questions become important and instructive. Consider the evolution of the ARCSS-funded FreshWater Integration study (FWI), a $30 million portfolio of 22 projects active from 2003 to 2009. (Arctic CHAMP, 2014; Vörösmarty et al., 2001). While focused on a single—albeit interconnected—component of the Arctic system, FWI emerged from a two-year planning phase specifically dedicated to formulating a community-based, integrated study of the Arctic hydrologic cycle as a system. FWI researchers united themselves around core research questions, first formulated in 2000–2001 yet retained for the duration of the project. The FWI science questions were all synthetic in nature, focusing on the evidence and direction of change, attribution and trajectories into the future. Additional synthetic "glue" was applied through five capstone studies, each one a multi-investigator undertaking uniting several FWI projects. Each of the capstones was an "experiment-in-synthesis" and represented an attack on fundamental systems-level questions that no single investigator or project could address easily on their own (Serreze et al., 2006, White et al., 2007; Francis et al., 2009a; Rawlins et al., 2010). These capstones were also highly collaborative, together convening more than 70 co-authors. These synthesis experiments spanned a wide range of topics including literature-based evidence of change, budgeting, acceleration of the hydrologic cycle, and heuristic modeling, some of which are explained in more detail below.

An even larger scope of planning, featuring many systems-level issues, can be found in the more recent Polar Research Board's *The Arctic in The Anthropocene: Emerging Research Questions*, published in 2014 (NRC, 2014). By its very name, it poses a wide variety of cross-disciplinary and fundamental questions that focus on five important interdisciplinary concepts: Evolving Arctic, Hidden Arctic, Connected Arctic, Managed Arctic, and Undetermined Arctic. Posing sufficiently clear but encompassing questions that can, in essence, be converted into testable hypotheses is at the heart of the research agenda proposed here in this report. In this way, existing or future investments in research programs, or even individual projects, can be summoned to support the needs of a broader research agenda, yet still be focused on grand-challenge issues that can create a motivating force across the research establishment. As highlighted in the PRB's report, the challenges are fundamentally systems-level in nature.

4.3. Inductive and Deductive Approaches to Synthesis

Arguably, a tension in the sciences may always have existed with respect to reliance on experimental/observational approaches (induction) or theoretical constructs (deduction) to develop an understanding of how systems work (Figure 4.3). (See also Section 1.3)

The *inductive* approach has numerous strengths, in particular the fact that any conclusions derived using this approach will be grounded in observations that document system state and trajectories. While subject to measurement error (as would any observation of the real world), observations nevertheless can be used to construct self-consistent explanations of system-level behaviors; that is, if the relevant data sets are available consistently and over sufficient time spans. This was, in part, an original justification for investments in the *Arctic Observatory Network* as well as for the *Sustained Arctic Observatory* (AON, 2018; SAON, 2018). The difficulty, however, is clear. When there are insufficient monitoring or experimental deployments—either over space, time, or components—the inductive approach will be based necessarily on a patchwork quilt of quantitative information, reducing the fidelity of any derived analysis. To compound the problem, the waxing and waning of particular data sets means that conclusions must be made on the incomplete spatial and temporal picture of particular phenomena. A good example is how precipitation gauge deployments over decades produce substantial differences in the spatial means of fluxes, consequently confounding any trend analysis (Figure 4.4) (Rawlins et al., 2006).

On the other hand, the *deductive* approach—used, for example, in the current generation of Earth System models—is at once potentially more sophisticated yet in all cases a simplified depiction of reality. Efforts to capture complex and nonlinear dynamics, while improving in skill over time, necessarily diverge, as simulations are run into the future based on different assumptions regarding how to depict the inherent processes and apply the variety of forcing factors.

In practice, what is needed is a combination of observational studies and modeling. It would be difficult to understand how a model could depict reality if its parameters, state variables, and fluxes did not bear at least some resemblance to observations in the real world. And it is perhaps equally

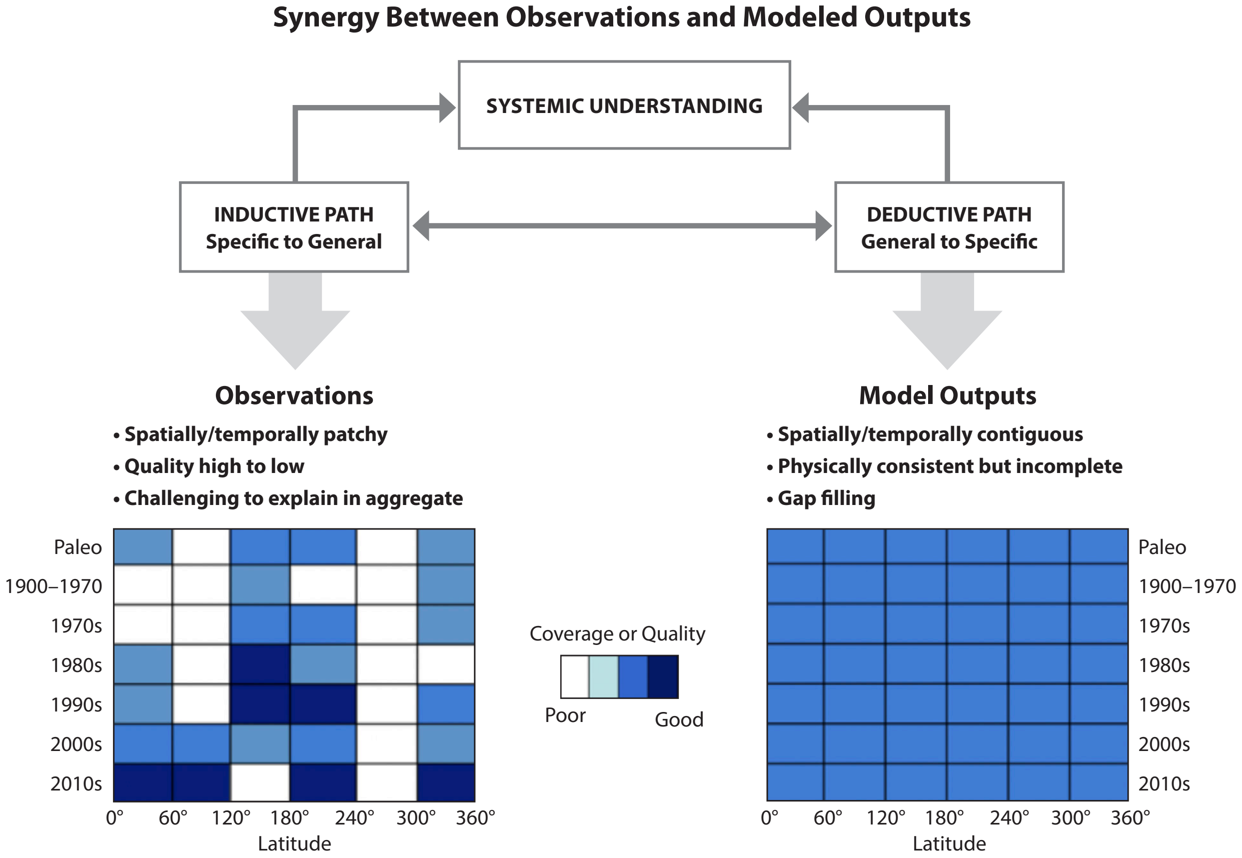


FIGURE 4.3. Elements of inductive and deductive thinking as pathways to systems-level understanding.

valid to state that observations fail to develop their full value to research without broader depictions of reality afforded by deductive processes or models—approaches that can test whether particular observations are plausible or evaluate how they fit into a broader context. Box 1.4, presented earlier, is an ideal example of how the two approaches can be combined to assess linked, system-level dynamics, in this case using the currencies of energy and freshwater in tandem.

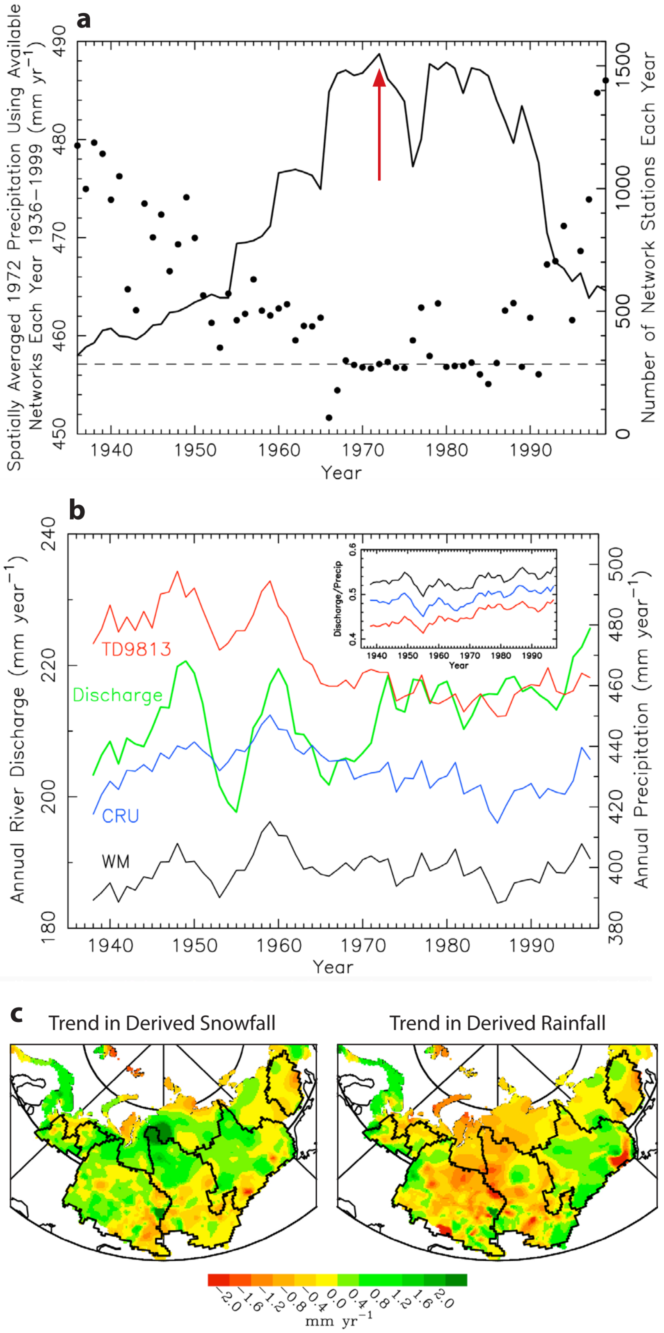


Figure 4.4. (a) Annual mean precipitation across the Eurasian pan-Arctic, benchmarked to year 1972 (dashed line represents spatially averaged precipitation for 1972), a year with the highest number of stations in the network between 1936 and 1999, and thus presumed to yield the most representative continental-scale mean. The points in the top panel show mean continental-scale precipitation year by year, interpolated using ground-based station network that was in place any particular year and forced by precipitation records from 1972. The time series of mean estimated precipitation is inversely related to the number of stations each year (solid line, right axis), reflecting the bias of deploying a higher number of sampling stations over wetter, more accessible domains (to the south). Precipitation time series trends (b) are counterintuitive relative to observed increases in continental discharge (Peterson et al., 2002). (c) Maps of the computed trends in interpolated snow and rain. The analysis argues for caution in interpreting trends solely on the basis of time-varying coverage represented by the observational record. From Rawlins et al. (2006); reprinted with permission, American Geophysical Union.

4.4. Establishing Fundamental Benchmarks

One focusing device to motivate Arctic system synthesis is to develop past, contemporary or future benchmarks, against which change can be detected and evaluated. These can take several forms, including literature reviews, budgets for individual or linked currencies, and data synthesis, including atmospheric reanalyses.

Literature Reviews. Comprehensive literature reviews are the mainstay of synthesis. One such review was executed for global change research in the early 2000s and promulgated through a book series published by the International Geosphere-Biosphere Programme (IGBP, 2018). If appropriately structured, the simultaneous consideration of an exhaustive archive of recent peer-reviewed studies forces the synthesis of otherwise “stranded” intellectual assets. For example, the compilation, harmonization, and interpretation of numerous Arctic paleobotanical archives and geological and limnological records enabled detailed reconstructions of past climates and ecosystem distributions to be made and compared to present-day conditions. This included the finding that today’s tundra-dominated landscapes had supported woody biomass, among other species range expansions, during the so-called Holocene thermal maximum, as well as extensive permafrost thaw (Walter Anthony et al., 2007), consistent with extensive warmth across the region (Alverson et al., 2003, Kaufman et al., 2004). National Academy Reports, like the *Arctic in the Anthropocene*, also relied heavily on comprehensive literature reviews, as did the *IPCC* and the *Arctic Climate Impact Assessment*. These two important assessments were based primarily on literature reviews that were not intended to constitute new research, but which nonetheless created new synthetic products in an attempt to understand connected, systems-level behaviors.

Constructing Constituent and Energy Budgets. Budget-building is also a convenient way to mobilize research that formulates systems-levels views of the Arctic (e.g., Lewis et al., 2000, Serreze et al., 2006, for water; Serreze et al., 2007, for energy). Physical oceanographers, atmospheric scientists, and hydrologists collaborated to synthesize understanding of the Arctic Ocean's large-scale freshwater (FW) budget. One capstone project (Serreze et al., 2006) incorporated terrestrial and oceanic observations along with outputs from atmospheric reanalysis and land surface and ice-ocean models (**Box 2.7**). The resulting budget for fresh water represented the best knowledge available up to the time of publication. The process of assembling and synthesizing this budget lent insight into the behavior of the integrated system while highlighting uncertainties in freshwater stocks and fluxes. The authors were able to identify the single largest flux of FW into the ocean (river runoff, 38% of the total input), quantify net precipitation (24%), and determine the importance of low-salinity inflows through the Bering Strait (30%). When paired with outflow estimates, there was an imbalance of annual FW flux of 700 km^3, within the error bounds of the data. Arctic Ocean freshwater had a mean residence time of about 10 years, contrasting with that for the atmosphere of only about a week. The team was unable to close the land budget or assess seasonality in Arctic Ocean FW storage, reflecting insufficient hydrographic and sea ice volume data. However, this budgeting exercise had an amplifying effect: There were many contemporaneous as well as follow-on studies that sought to reduce the uncertainties in these estimates in the ocean, atmosphere and terrestrial domains (e.g., Rawlins et al., 2010; Woodgate et al., 2012; Zhang et al., 2012).

Baselines through Data Synthesis. Budgets and flux studies are difficult enough for one currency, let alone multiple constituents controlled by energy and biogeochemistry. This is also difficult when the contributing data sets cross disciplinary divides, with different boundaries, resolutions and terminologies (e.g., atmospheric variables versus population census tract data versus wildlife inventory data versus remotely sensed sea ice). (See **Figures 1.5, 4.1, and 4.2**). In addition, when source data are assembled in a geographic framework, new insights can be gleaned into the character and quality of the derived information. This is precisely what emerged when in situ Eurasian precipitation data were assembled, used to derive precipitation fields and then numerically analyzed (**Figure 4.4**). Lower gauge densities were associated with a generally higher domain mean, resulting from biased sampling of the southern portions of the continent that generally experience wetter conditions. This, in reality, was merely a sampling bias. Maximum gauge density occurring in the early 1970s sampled the region more evenly and corresponded to what appeared to be a minimum in the domain mean (at least on an annual time step). The improved spatial representation of conditions across the northern portion of the domain with its more xeric, continental climate reduced the overall mean. Placing this into still broader context, the apparent trends were decoupled from discharge records over the same period. An affiliated attribution study (Rawlins et al., 2009b), which assembled multiple and sometimes redundant data sets to trace a climate anomaly as extreme river flows passing through a Eurasian drainage basin on its way to the sea, is another example of a data synthesis effort, working in part off this baseline of precipitation (see **Box 3.2** for analysis of a North American counterpart).

4.5. Heuristic Studies: Hypothesis-Generating Thought Experiments

Hypothesis-testing is the mainstay of science and the hypothesis-generation phase of any new study is an important time for researchers to crystallize the scope and character of the phenomena they are about to examine. Scientists must first acknowledge a set of baseline principles and facts—including the newly uncovered—upon which a new process, a quantified state, dynamical interaction or other relationships can be built. Such stage-setting can be used in the design of laboratory or field experiments, to posit the outcomes of any new integrated data sets (as discussed throughout this chapter) or predict the plausible responses of digital models to the conditions being tested through the hypothesis.

A hypothesis-generating exercise cast at the full Arctic systems-level was pursued by Francis et al. (2009a). It employed a heuristic, graphical synthesis (initiated by Overpeck et al. 2005), focused on how changes in the pan-Arctic hydrologic system ultimately could affect life in the ocean, life on land, and human society. The conceptual framework reduced the complexity of the problem by applying a stepwise logic that first identified key system components, established the major linkages between them, and then extracted the presence and sign of feedback loops, i.e., positive (self-reinforcing) or negative (system-dampening), all guided by literature-based findings and the intuition of the study team that included observationalists and modelers. One of the resulting "wiring diagrams" is presented in **Figure 4.5**, showing a postulated set of connections among increasing air temperature, sea ice loss and ocean heat storage, which in turn affects marine productivity and human well-being, but in competing ways. When published in 2009, this study underscored the uncertainties characterizing these relationships as obstacles to understanding Arctic system change, with many of these questions remaining to this day.

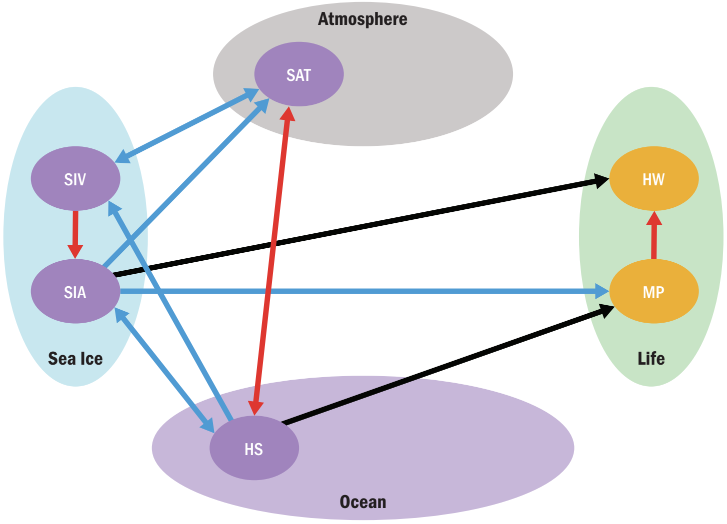


FIGURE 4.5. Example of a systems-level hypothesis regarding feedbacks in the Arctic's marine system. Note inclusion of geophysical, biological, and human dimension elements. This particular, poorly understood feedback links sea ice through ocean heat content to marine productivity and human wellbeing, highlighting competing effects on living systems. Arrow colors indicate signs of interactions, with red (blue, black) arrows denoting interactions of the same (opposite, competing) sign. Hub colors indicate drivers (purple) versus recipients of impact (orange). SAT = surface air temperature. SIV = sea ice volume. SIA = sea ice area. HS = ocean surface heat storage. HW = human well-being. MP = marine productivity. After Francis et al. (2009a).

4.6. Full-System Modeling

The Arctic in Global Circulation and Earth System Models

The evolution of Earth system models has progressed steadily in terms of their spatial and temporal resolutions as well as the degree to which individual processes and linkages (e.g., land-atmosphere, atmosphere-ocean) are represented (Seitzinger et al., 2016). Along these lines, GCMs are being improved to simulate cryospheric processes, and the Polar Climate Working Group of the Community Climate System Model (CCSM) is an example of a community-based effort to bring Arctic dynamics into the realm of global modeling and better understand how the polar climate system has reciprocal, complex interactions with the lower latitudes. This has included contributions from researchers within both university and government laboratory communities. Having a full-scale modeling framework (ESMF, 2017) enables researchers to address diverse model applications, from improving our understanding of high-latitude paleoclimate processes to evaluating the impacts of a retreating Arctic ice pack on wildlife.

Regional Arctic System Modeling

The understanding of polar regions has advanced tremendously in the past two decades (Jeffries et al., 2013) and much of the improved insight is due to multidisciplinary and interdisciplinary studies conducted by coordinated and collaborative research programs supported by national funding agencies. Although much remains to be learned with respect to component processes, many of the most urgent scientific, engineering and social questions can only be addressed through the broader perspective of studies on system-level scales. Questions such as quantifying feedbacks, understanding the implications of sea ice loss to adjacent land areas or society, resolving future predictions of ecosystem evolution or population dynamics all require consideration of complex interactions and interdependent linkages among system components and sub-components. Research that has identified physical controls on biological processes, or quantified impact/response relationships in physical and biological systems is critically important, and must be continued (Overland, 2016); however, we are approaching a limitation in our ability to accurately project how the Arctic will respond to a continued warming climate. Complex issues, such as developing accurate model algorithms of feedback processes, require higher level synthesis of multiple component interactions and thus the need for complex system models that include a wider variety of processes (Roberts et al., 2010, 2011; Heavens et al., 2013) (Figure 4.6).

Arctic System Models simulate impact, response, and feedbacks of the relevant and interdependent processes through dynamically coupled algorithms (Cassano et al., 2017). Such models enable analysis of higher order effects of an evolving system. It is not possible to fully capture climate transitions, ecosystem response, and simultaneous influences back to the climate without incorporating the essential components of the system (Maslowski, 2013). The newly developed Energy Exascale Earth System Model (E3SM) project addresses the need to couple Earth system processes on a global scale (DOE, 2018) and marks a promising pathway to future analyses of climate trajectories and ecosystem responses. In so pursuing a more complete vision of the Arctic system, an evolutionary framework is needed to adopt new component process models as they become available, along the lines of what has characterized the climate and Earth system modeling community more generally over a multi-decadal development period (Figure 4.7).

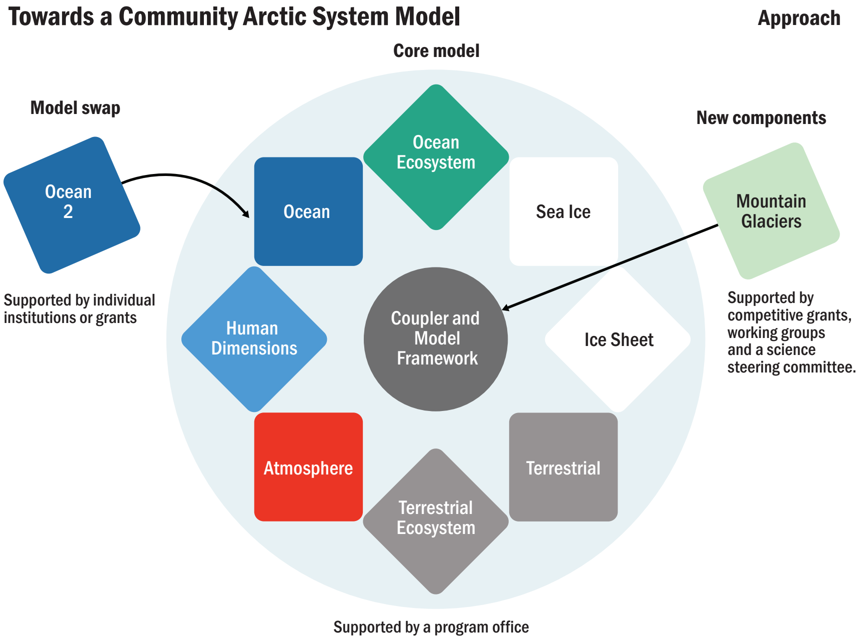


Figure 4.6. Full-system simulation framework for studying the Arctic. Note the modular framework, which enables community inputs that result in process-level simulation improvements. Courtesy of ARSC/IARC.

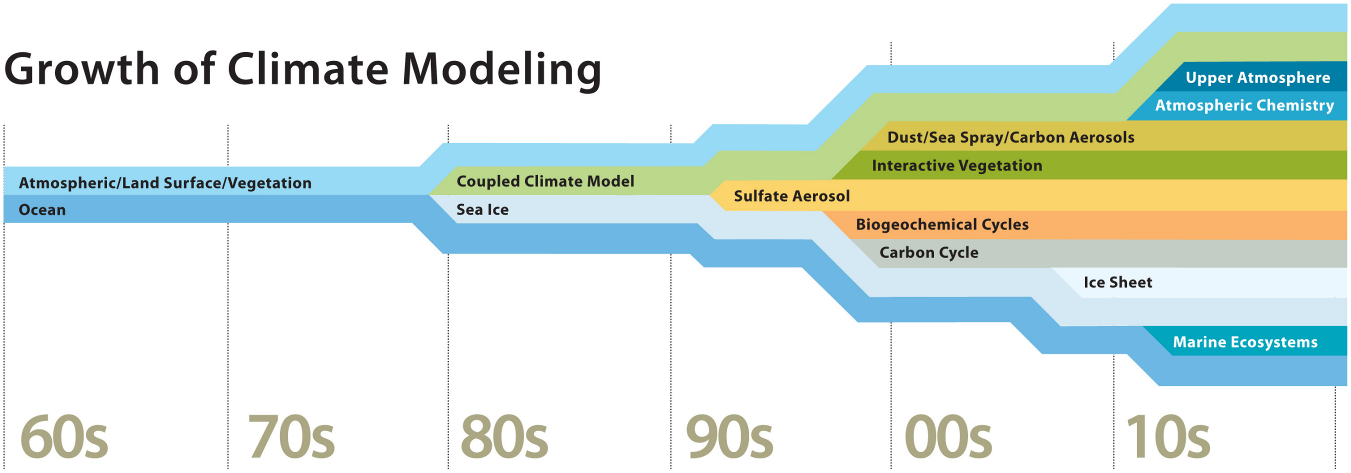


Figure 4.7. Progress toward more comprehensive climate models has progressed systematically and in tandem with computational capabilities and knowledge generation. Several Arctic processes or phenomena that control the climate system of the Arctic (e.g., sea ice, ice sheets, interactive vegetation, aerosols) are evident in such global models and have helped propel their development. A similar evolution would be envisioned for Arctic system model development per se. From UCAR (2018).

Atmospheric Reanalysis

An atmospheric reanalysis is an historical time series of the three-dimensional state of the atmosphere, including surface fluxes, that is developed by assimilating observations within a numerical weather prediction framework. The observations largely comprise “free atmosphere” variables, such as temperature, wind and pressure at different levels in the atmosphere obtained from weather stations, radiosondes, dropsondes, satellite retrievals and aircraft reports. Most modern reanalyses provide data starting in 1979 (the beginning of the modern satellite era), and extended reanalyses going back a century or more are based on assimilation of only surface observations. Reanalysis fields can be broadly divided into what are known as *analyzed fields* (examples being pressure heights, temperatures, humidity, and winds), in which observations directly affect the output, and those for which observations do not directly affect the output (sometimes called *modeled fields*). Examples of the latter include surface radiation fluxes, turbulent heat fluxes and cloud cover. Variables are interpolated to a regular 3D grid and depending on the system, are available from twice daily to hourly. At least half a dozen reanalysis efforts are ongoing at present under the auspices of NOAA, NASA, the Japan Meteorological Agency, the European Centre for Medium Range Weather Forecasts, and The Ohio State University (Saha et al., 2010; Dee et al., 2011; Bosolovich et al., 2017; Gelaro et al., 2017).

Reanalyses have revolutionized climate research because they allow one to easily assess atmospheric and surface conditions in the historical past and compare them to average conditions or conditions at other times. In recognition of large data volumes, some producers have developed analysis tools to help users. *Analyzed fields* depicted in different reanalysis systems tend to agree fairly closely with each other because they are based on nearly the same assimilated data, while there is typically a wide disparity between different systems in their depiction of *modeled fields*. In any study making use of modeled fields, it is general practice to look at outputs from several different reanalyses in order to provide a sense of the spread, or uncertainty, in the values (e.g., Lindsay et al., 2014). Given this interplay between observations and models, the approach is an example of a combined inductive-deductive approach (**Section 4.3**).

Subsystem Process Modeling

Recognition that seasonal changes in soil water and ice content are important components of Arctic hydrology (Woo et al., 2008) has led to the modification and development of numerical climate/land surface/hydrological models that incorporate the ice-dominated dynamics (Cherkauer et al., 2003; Nicolsky et al., 2007; Niu and Yang, 2006; Rawlins et al., 2013; Ganji et al., 2017). Land surface hydrology models are a case in point, and emblematic of developments in other domains of currency studies. These models have been used in "offline" mode; that is, forced with atmospheric data, to simulate Arctic streamflow and river discharge, and they range from simple water balance models to lumped parameter and large-scale distributed 3-D models. They are intrinsically geospatial and aim to capture the high prevalence of wet surficial soils and surface water; hydrology models operating across the high northern latitudes usually include the seasonal thawing and freezing of soils. The inclusion of freezing soils in model simulations will typically increase the ratio of runoff relative to precipitation and produce greater amounts of surface runoff following snowmelt compared with models lacking this detail, often resulting in runoff that compares more favorably with observations (Niu and Yang, 2006; Ganji et al., 2017). Simulations from fully coupled atmosphere-ocean general circulation models (AOGCMs) are also being used to project how runoff and river flows—key elements of the water balance of the Arctic—may respond as the climate warms (Kattsov et al., 2007; Holland et al., 2007; Wu et al., 2005).

Models that are suitably physically scaled and tailored specifically for studies of the Arctic freshwater cycle are useful for understanding connections among processes controlling runoff generation and river discharge export, then linking to other currencies. An example is the Pan-Arctic Water Balance Model (PWBM), which simulates all major elements of the Arctic water cycle, including snowfall and storage, sublimation, transpiration, and surface evaporation (Rawlins et al. 2003, 2013). Snowpack dynamics are simulated with a multi-layer snow model that accounts for wind compaction, change in density due to fresh snowfall, and depth hoar development over time. Soil temperature dynamics are simulated by a 1-D nonlinear heat equation with phase change (Rawlins et al., 2013). Such hydrologic system models have demonstrated a high degree of versatility. In the case of the PWBM, it has been used to investigate causes behind the record Eurasian discharge in 2007 (Rawlins et al., 2009b); to corroborate remote sensing estimates of surface water dynamics (Schroeder et al., 2010); and to quantify present and future water cycle changes around Nome, Alaska (Clilverd et al., 2011). Simulations coupled to a dynamic soil carbon model can capture the influence of snow cover and soil thermal dynamics on the seasonal and spatial variability in soil carbon dioxide respiration (Yi et al., 2015).

4.7. Reduced Complexity Modeling

One approach to using models to advance synthesis is to build complexity into state-of-the-art Earth system models (Roberts et al., 2010). While ultimately necessary to improve climate predictions at fine spatial and temporal scales (Petoukhov et al., 2005), adding complexity can also hinder synthesis (Laprise et al., 2008; Chan et al., 2012). Additionally, a widely used Earth System Model (CCSM) typically runs at 1° horizontal resolution with 26 atmospheric layers, 60 in the ocean, and 15 in terrestrial soils (Gent et al., 2011; Lawrence et al., 2012), and uses large allocations of computing time requiring access to supercomputers with thousands of processors, and trained specialists running specialized software. Such requirements limit the capacity to rapidly probe the internal dynamics and sensitivities of the system, hindering traceability of cause-and-effect.

The current approach of building ever more complex and computationally expensive Earth system models could be productively complemented by simpler process-based tools, especially during the early stages of probing how the basic system components interact (i.e., Arctic atmosphere, ice, ocean, land). Using this approach, a high degree of accuracy may not be assured (or even sought). Yet such models enable rapid testing of hypotheses insofar as the model structures are designed to capture general dynamics—the direction and hierarchy of response in lieu of six-digit accuracy. Simplified formulations depicting the structure, strength of interactions and parameterizations linking natural and policy sciences, economics, and policy can rapidly be assessed in terms of their utility and, if deemed insufficient, can then serve as the basis for more sophisticated simulations using the lessons learned from the more simplified analysis (**Figure 4.8, Box 4.2**).

Given that frameworks are still needed to assess how human actions, and not just biogeophysics, shape the behavior of a linked Arctic system, another important characteristic of this more simplified approach is its capacity to assess how alternative human decisions ultimately feed back to the Arctic (if not global) system. *What, for example, would be the consequence of black carbon mitigation in boreal forest management?* This becomes particularly valuable in the context of scientists attempting to interact with policymakers and environmental

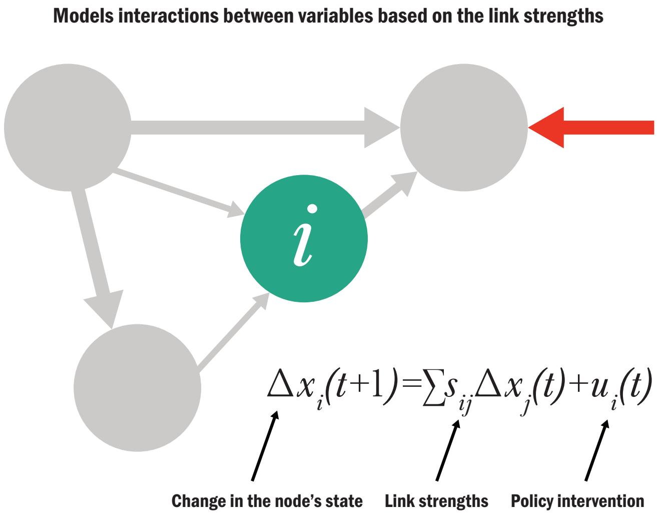
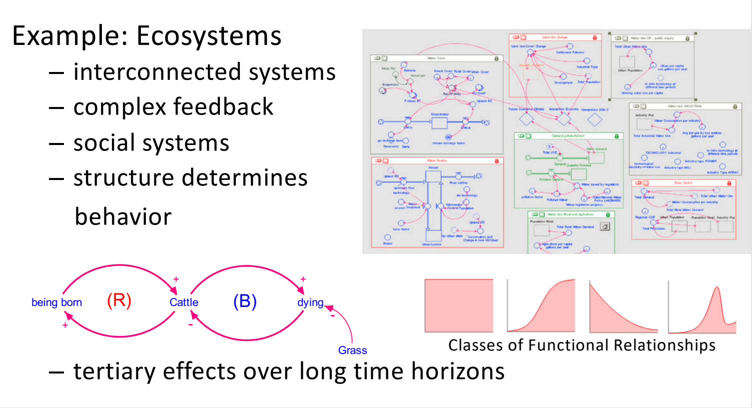


FIGURE 4.8. A simplified formulation for exploring state variable interactions with policy interventions in a simplified model setting. From E. Rovenskaya, IIASA.

BOX 4.2. Capturing the Key Dynamics in Reduced Complexity Models

Social policy planning is challenged by the context in which it is exercised, for example constrained by government (or business) regulations and structure, a "silo mentality," and urgent timeframes. Often little or no quantitative data may be available, and a trial and error approach is not possible. Can models be useful? Yes, if they are fully understandable, trustable, interactive, and serve decision-making. The co-design of a model together with stakeholders is key (Rosenzweig et al. 2014). If there are stringent time limits, in order to enable those involved to make the most out of their interactions the use of visual images and on-line tools in an interactive/participatory process has obvious advantages. Over a series of projects, the *Advanced System Analysis Program* (at the *International Institute for Applied Systems Analysis*; IIASA) has examined a range of topics from regional economic growth to refugee migration. The efforts first involved developing "system maps" using a system dynamics approach. In a systems map, the choice of variable and the depiction of its interactions with its counterparts depend on the particular research question at hand, with model interactions between variables based on the strength of their linkages (**Figure 4.8**). A multiplicity of experts often produces a plurality of views. To engage stakeholders, definitions of variables and processes must be as clear as possible and uncertainties must be understood by providing for error detection and outlier removal. Policy experts usually find this to be an enlightening approach.



Example: Ecosystems
- interconnected systems
- complex feedback
- social systems
- structure determines behavior
- tertiary effects over long time horizons

A Modeling Platform to Assess Human-Environment Interactions. The iSEE systems platform enables simple to medium complexity models to be formulated, with rapid response times, ideal for engaging users to explain system-level structures and behaviors as well as to jointly (with researchers) formulate scenarios and "what-if?" experiments. Such a capability is not possible with full complexity models which, while arguably more complete and accurate, are far more demanding in terms of set up, computational requirements, and run-times. From K. Chichakly, iSEE Systems.

managers. Simplified, rapid run-time models could be productively exercised in scientist-stakeholder workshops, with what-if scenarios formulated and run, effectively on the spot—a practical impossibility for researchers attempting to employ full-complexity models. Such a scenario-building approach is currently being planned as part of the Arctic Futures Initiative under the aegis of the International Association of Applied Systems Analysis (IIASA AFI, 2018) and within the Study of Environmental Arctic CHange (SEARCH) program.

4.8. Use of Experimental and Observatory Data

An effective interplay between observation-based induction and deductive modeling as described in **Section 4.3** requires that a sufficient backbone of quantitative as well as qualitative information be available to effectively pursue synthesis (**Box 4.3**). There is a huge scope of existing and anticipated observatories across the region (AON DITF, 2012)—including new monitoring networks, advanced autonomous vehicles, in situ sensors, field experiments, remote sensing and affiliated field campaigns. The discussion that follows first treats observations over the pan-Arctic domain followed by smaller-scale regional and field station experiments.

Pan-Arctic Data Sets. There are a variety of openly available data resources that provide observationally based measures of system variables over the full pan-Arctic domain, based on interpolated in situ and satellite-borne data resources (e.g., **Figure 4.9**). Many of these observatory data sets are well established and available through the Advanced Cooperative Arctic Data and Information Service (ACADIS) and other Arctic Observing Network (AON) data repositories (Moore et al., 2013). A multitude of pan-Arctic domain data sets are also available at NASA, NOAA, and USGS data archive centers as well as from non-U.S. sources (e.g., ESA). Legacy and ongoing satellite data sets (e.g., Landsat, SSMR, SSM/I, AVHRR, MODIS, VIIRS) provide long time series observations supporting both research and operational measurement needs, and can aid studies into issues relating to interannual variability across multiple years and climate oscillations. More recent and planned satellite-borne satellite systems (Sentinal-1/2/3, NISAR, ICESat-2) are establishing a proliferation of new data sets that will now be routinely available. Open access data policies that have developed across agencies are promoting routine data sharing and integrated synthesis studies. At the same time, such diverse data sets are not necessarily harmonized or well-integrated. Hence, a significant data assembly and staging effort will be required to advance synthesis efforts.

Box 4.3. Using Integrated Data Resources in the Systems Setting

A hypothetical example of how integrated data compendia could be used to advance synthesis and systems-level understanding is instructive. Imagine a pan-Arctic study of sea ice-generated feedbacks on ocean productivity, which necessarily must enlist the inputs of multiple disciplines across the Arctic research community.

First, an appropriate data management support system is assumed to exist to facilitate multiple data-layer discovery, which can then be combined spatially and temporally to identify and explore synergistic interactions. Using data discovery tools to rapidly canvass developments across the different disciplines within the community (even outside the Arctic), and performing a comprehensive literature review of prior research, the research partners easily locate critical data sets. In their search for relevant data they discover that a new, high-temporal-resolution sea ice time series is available, unexpectedly repurposed from a soil moisture remote sensing system. NASA's Soil Moisture Active Passive (SMAP) mission is one example (Entekhabi et al., 2010). Given the publicly available nature of many Arctic observational data sets, the digital information is then secured, vetted, and delivered to users across the community. By "digitally engaging" researchers in this way, the partners find several additional uses for these data, including applying them to build energy budgets, where project scientists simultaneously discover a useful atmospheric reanalysis product. In turn, that data set is shown to have further value when combined with open water estimates from the SMAP-derived sea ice coverage and carbon uptake estimates from ocean optical imagers (NASA, 2018). The unique data combination—which brought together atmospheric scientists, sea ice experts, biological oceanographers, and remote-sensing experts—enabled them to search for and develop relationship relationships linking water-energy-carbon at the pan-Arctic scale using pattern recognition tools (Chen and Ho, 2008).

A similar process could be envisioned using field campaign experimental data, which will be particularly useful for specifying process-based relationships for both full and reduced complexity models. Such data experiments can also be used to support ongoing observatory design activities (AON DITF, 2012). A discussion of large field campaigns is given below and in **Box 4.4**.

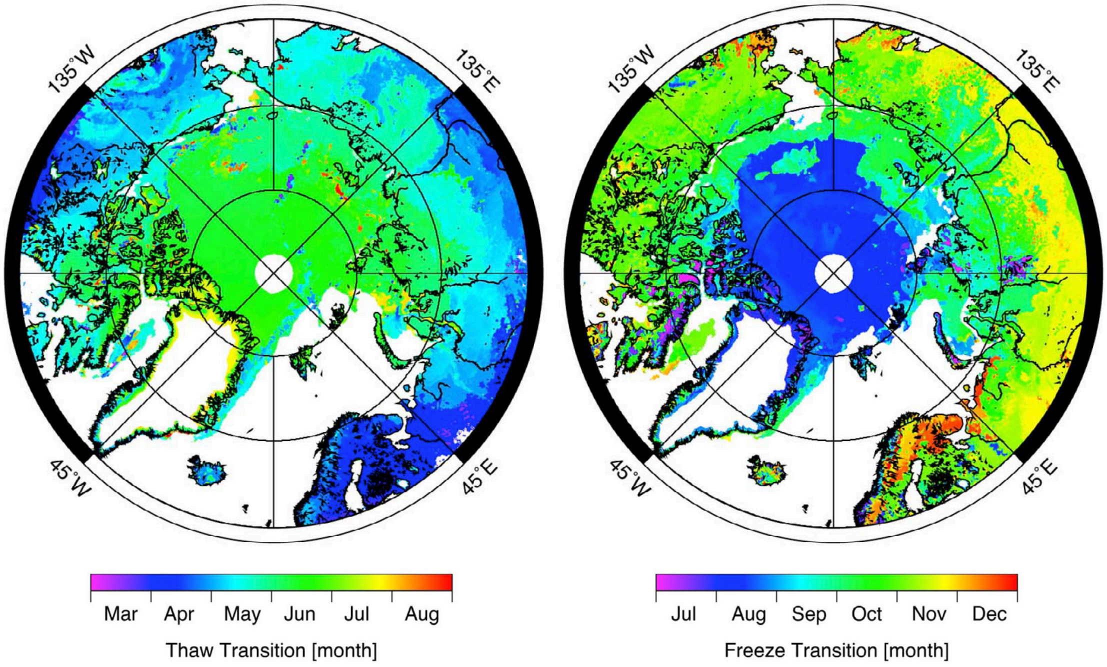


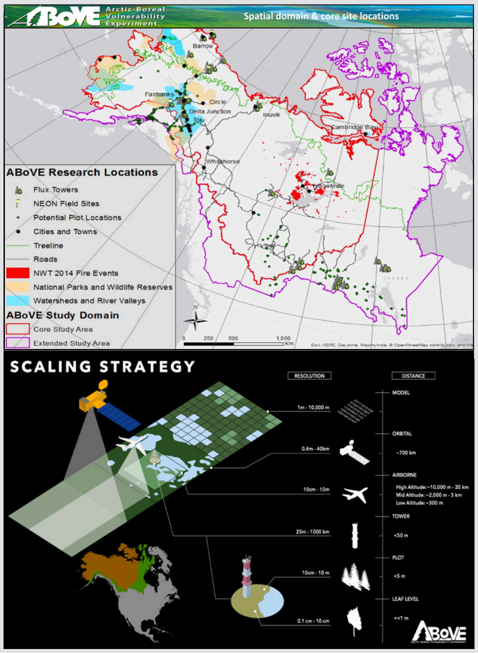
FIGURE 4.9. Maps of springtime thaw transition (left) and autumn freeze transition (right) derived from resolution-enhanced SeaWinds-on-QuikSCAT backscatter over the north polar land and sea ice domain for 2006. This unique synoptic map of seasonal transitions across the Arctic land-ocean domain demonstrates new capabilities for combining satellite remote sensing data sets for improved retrievals of Arctic biogeophysical properties. From Mortin et al. (2012); reprinted with permission.

Integrated Field Campaigns. Many well-funded field programs seek to understand various aspects of the Arctic system, but no single effort has been initiated to draw these projects together toward a common goal (Box 4.4). Examples of research programs that have pursued "targeted" syntheses include: DOE-NGEE (Next Generation Ecosystem Experiment), NASA-CARVE (Carbon in Arctic Reservoirs Vulnerability Experiment), ABoVE (Arctic Boreal Vulnerability Experiment), NASA's IceBridge and Oceans Melting Greenland (OMG), and the U.S. Fish and Wildlife Service's Arctic-LCC (Arctic Landscape Conservation Cooperative). The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) program is planned as the first year-round expedition into the central Arctic in the "New Arctic" era to gain insights into the causes and consequences of an evolving and diminished Arctic sea ice cover on the climate system. The effort will investigate the seasonally varying energy sources, mixing processes, and interfacial fluxes that affect the heat and momentum budgets of the Arctic atmosphere, ocean and sea ice. The multi-agency Study of Environmental Arctic Change (SEARCH) program offers perhaps the greatest opportunity for such integration. The SEARCH action teams that have the most obvious linkages include: land-ice (focused on factors affecting sea level rise), sea ice (focused on impacts of sea ice loss), and permafrost (focused on the carbon cycle and impacts of permafrost thaw). All are major, multi-year initiatives to enable variability to be characterized, trends to be detected, and cross-connecting impacts to be assessed both within and beyond the Arctic.

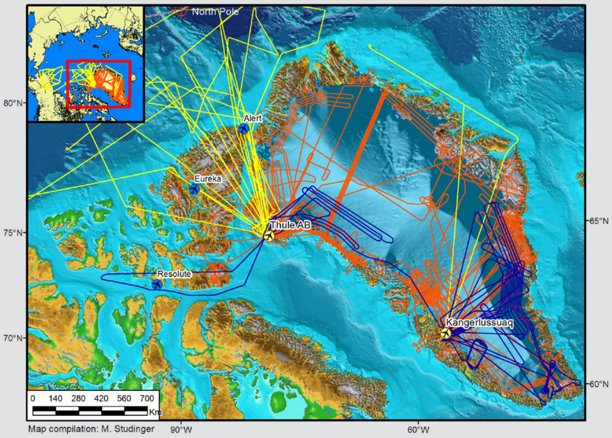
The data emerging from large field campaigns are important in several ways. First, they have clear application as calibration-validation data sets for any model development. In such a data-rich, localized environment, researchers are able to stage numerical experiments in which models are sequentially configured with increasing levels of detail and then tested against actual field data (AON DITF, 2012). They are then able to determine the bounds and components of uncertainty, whether at the process or system level. This, in turn, informs model developers on the sensitivity of model results to the level of process representation and temporal or spatial aggregation, and suggests strategies for scaling-up from field to broader domains (USARC, 2010).

Box 4.4. Three Biogeophysical Field Campaigns

The *Arctic Boreal Vulnerability Experiment (ABoVE)* is a large-scale NASA-led study of environmental change in Arctic and boreal regions and the implications for ecological systems and society. Its overarching science question is fundamentally systems-oriented: *How vulnerable or resilient are ecosystems and society to environmental change in the Arctic and boreal region of western North America?* The *ABoVE* domain encompasses much of western North America and includes a wide range of field sites. *ABoVE* airborne intensive observing periods (2017 & 2019) will (1) provide domain-wide context to unify site-level process studies, (2) link to satellite remote sensing to interpret large-scale signatures of change, and (3) demonstrate new remote sensing technologies and multi-sensor data analyses. A scaling strategy employed during *ABoVE* will leverage ground and airborne measurements, orbital remote sensing, and modeling to bridge scales from <1 m to the continental domain. The science team includes approximately 75 PIs (NASA and affiliated) and 500 investigators and collaborators from more than 150 organizations and a variety of disciplinary perspectives. *ABoVE* is ultimately about coordinating and facilitating transdisciplinary science in a resiliency/vulnerability framework. Several coordinating working groups include those for vegetation dynamics, fire disturbance, carbon dynamics, hydrology and permafrost, and modeling. Research within *ABoVE* is helping to answer important questions regarding the connections between linked currencies, for example, how future vegetation distribution changes will alter albedo, energy balance, and nutrient and carbon budgets.



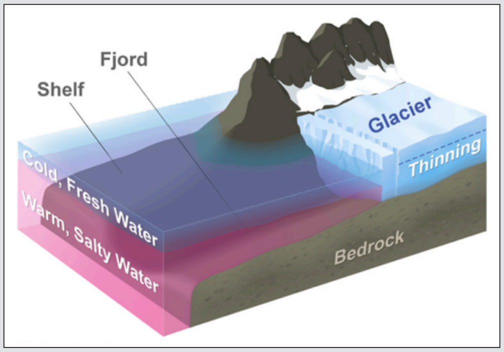
Project domain and cross-scaling to achieve coherency of data across local to subcontinental domains. From NASA/ABoVE.



Flight tracks showing regions covered by aircraft-mounted instruments during the 2012 IceBridge campaigns in the Arctic. IceBridge Arctic campaigns have been ongoing since 2010. Complementary campaigns have been ongoing since 2009 in the Antarctic. From NASA (2018a).

Another remote-sensing-based campaign is NASA's Operation IceBridge, which collects airborne measurements to fill the gap in measurements between the end of the ICESat-1 mission and the launch of ICESat-2 (Koenig et al., 2010; Studinger et al., 2010). IceBridge has been providing surface elevation data since the end of NASA's ICESat-1 mission, focusing on areas critical to characterizing sea ice and to modeling the processes that determine the mass balance of the terrestrial ice sheets. IceBridge also supports complementary measurements critical to ice models, for example, bed topography, grounding line position, and ice and snow thickness. These parameters cannot be measured by satellites but can be from aircraft and are part of significant unknowns in developing predictive models of sea level rise in response to climate change. IceBridge has built upon the data collections begun with ICESat-1 and enabled scientists to better understand how a changing climate affects polar ice. IceBridge data have improved knowledge of the topography of bedrock beneath ice, shown that glacier thinning rates have increased, allowed researchers to predict future glacier discharge speed, and have been critical in efforts to validate data gathered by the European Space Agency's CryoSat-2.

Similarly, NASA's Oceans Melting Greenland (OMG; Morlighem et al., 2016) examines sea level rise linkages to the coastal glacial mass balance by using specialized measurements focused on assessing ice surface topography and coastal bathymetry, and modeling ocean-ice interactions to estimate the extent to which the ocean is melting Greenland's ice from below. Such objectives as addressed by IceBridge and OMG are achievable only though orchestrated, intensive field campaigns.



A typical marine glacier in Greenland, with cold, fresh water near the surface and a layer of warm, salty water below. Over a five-year campaign, Oceans Melting Greenland (OMG) will measure the volume and extent of this warm layer each year and relate it to thinning and retreat of the glaciers. From NASA/JPL (2018).

CHAPTER 5. SYSTEMS SCIENCE SUPPORTING POLICY AND MANAGEMENT

The large number of examples of Arctic change given throughout this document attest to the need for an appropriately designed science agenda that integrates across disciplines to understand the drivers, their interactions, and likely future trajectories of this complex region—the essence of synthesis and systems-level thinking.

Understanding the biogeophysical changes alone constitutes a critical research challenge and will occupy the Arctic research community for years, if not decades, to come. However, the changes are not restricted to the domain of basic science, and they reverberate into many societally relevant arenas (Table 5.1). These include 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, fires and smoke affecting navigation and infrastructure, and the loss of species, including those upon which traditional hunting/fishing depends. Although there will be many positive effects of a changing Arctic domain, including access to new trans-Arctic ocean shipping routes, resource extraction, and new fisheries, there will also be costly negative impacts that interfere with human activities and undermine economic development across the region.

Due to the compelling risk of Arctic system change and extreme events on human well-being, one would expect a clear call-to-action by policymakers and other stakeholders to scientists for decision support. Yet, several challenges conspire to limit the clarity and timeliness of the research community's response to this knowledge demand. First, there are fundamental systems-level questions that remain to be answered and could be interpreted as the incapacity of the research establishment to be responsive. While questions abound in the domain of Arctic system science (Chapters 2 and 3) and while they argue still further to improve fundamental systems-level research, there are also useful systems-level approaches available for policy support (e.g., models and structured decision making in support of the Endangered Species Act). New paradigms of scientific inquiry also require sufficient time to be assimilated

TABLE 5.1. Examples of key societal domain issues, together with potential contributions from the Arctic system sciences. After USARC (2010).

ARENA OF INTEREST	EXAMPLES OF SUPPORTING SYNTHESIS PRODUCTS
Climate Change and Human Health	• Systematic health state monitoring • Statistics and analytics to map and upscale to determine large-scale patterns and correlates
Climate Adaptation and Mitigation	• Improved Arctic domain Earth system models for climate forecasting and land/ocean biospheric carbon dynamics • Integrated assessment models to evaluate the economic and other human-centered impacts of Arctic-focused actions
Infrastructure Vulnerabilities	• Systematic, geo-registered infrastructure inventories (private and public) • Biogeophysical-economic analysis to predict depreciation • Scenarios of risk across the pan-Arctic domain using system modeling forecasts
Subsistence Harvest and Commercial Fisheries	• Habitat fragmentation mapping in response to pan-Arctic terrestrial and oceanic change • Systematic tracking and forecasts of key species distributions and their interactions with habitat and food resources across the key Arctic biomes • Resource management plans to accommodate future system-level changes
Non-Renewable Resource Extraction	• Harmonized data inventories and geospatial distribution maps • Environmental risk assessment of extraction under rapid change
Ice Navigation	• High fidelity, multiscale ice distributions: near-real time and forecasts • Integrated observation-modeling system using state-of-the-art technologies for navigation and operations in ice-dominated waters
Oil Spill Response and Restoration	• Improved wind and current vector monitoring and prediction • Analysis of sensitivity (lethal/sublethal) exposure and effect of oil on food webs and other environmental systems • Source-path-fate models of oil through physical and chemical dispersal, entry into and through biotic systems

into the mainstream research community, which in turn will provide the necessary levels of proof and reduction of uncertainty for improved decisions (Cohen, 2015).

In addition, and in contrast to instant information transfer through news outlets and social media that substantially defines public perceptions of need, the process of information gathering to substantiate facts is slow. This is in good part because the process must be guided by the necessary caveats associated with scientific findings. A consequence is that the process itself contributes to reducing the level of urgency to act among policy and decision makers (Vörösmarty et al. 2015). Furthermore, the timescales of many of the societally relevant impacts—sometimes centuries or millennia into the future—place the formulation of policy actions far off the radar screen of any politician seeking reelection, or any homeowner contemplating purchase of a home on the shoreline. Because human actions are driven by exigency and immediacy, investments to protect future generations can be significantly delayed, despite warnings of imminently moving past a point of no return (Holland et al., 2010; Schellnhuber, 2009).

Additional impediments involve complex and inertia-laden bureaucracies, from which messages to the research community become difficult to coordinate. Federal Arctic research is a good example of how multi-agency interests could benefit from better coordination but face inherent obstacles to achieving that goal. In the United States, because there is no single office for science, agencies set their own agendas, based on historical precedent, guidance from the administration and Congress, and on their own interpretation of their mission and objectives. Thus, many forces shape the agenda of any single agency, including the legacy of the past year's budget, coordination from OSTP and NSTC, OMB, as well as Congressional fiscal directives, agency heads and staff, external advisory bodies (e.g., National Academy of Sciences), and internal planning activities.

In this context, a sequence of executive orders in previous administrations (Bush, 2009; Obama 2014, 2015) sought to establish a more coherent set of national policies for the Arctic, recognizing its growing strategic and economic importance to the nation. Another tangible example of how the integration and synthesis of research products can be used in the public policy domain was Executive Order #13580, issued on July 12, 2011, establishing the Alaska Interagency Working Group to help coordinate the numerous federal agencies involved in energy development and permitting in Alaska. Later, a Deputy-level Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska (Clement et al., 2013) was convened. Its task was to integrate all relevant government and (where possible) private sector data sources relevant to the offshore energy permitting process in the Chukchi and Beaufort Seas outer shelf—essentially creating a ready-made audience and demand for scientific information. Many of the variables, indicators, and metrics essential to the offshore permitting process are in fact those that are also generated by the research community, including baseline inventories depicting the region's oceanography, climate, geology, and biology as well as the dynamics of land, atmosphere, ocean subsystems and the associated environmental sensitivities. Such information is recognized as precursor to a much-needed systems-level understanding to improve decision-making in Arctic energy resource development (Holland-Bartels and Pierce, 2011).

Thus, when scientific information is actively sought by decision-makers, focused clearly on the interests of the parties seeking such data, and made relevant to constituencies that ultimately fund the research, there is a better chance that the information will actually be used by stakeholders. But this requires reciprocal interactions among knowledge providers and consumers. In this context, information consumers need to be informed regarding emerging arenas of concern by the knowledge holders. It is also important to identify the readiness of the research and assessment community across a wide spectrum of applications. Identifying and filling key gaps in science and technology readiness today helps to forestall delays in acquiring policy-actionable knowledge upon which future adaptation strategies—for climate, environmental and social system change—can be based. This requires open dialogue and co-design of a shared research agenda (**Box 5.1**).

What might such a process look like? First, it would represent a more complete alliance of natural and social scientists, decision-makers and the private sector working together through a co-design process for policy and environmental management (**Figure 5.1**). By co-design we mean the relevant interchange of information needs of stakeholders aired in a suitable forum to be received and understood by knowledge providers representing the research community. The process next formulates a dialogue to refine those information needs and critically assess the feasibility of the state of the art in science to deliver upon those requests. This is embedded within an iterative process of adaptive management, which ultimately reconciles the original differences in points of view and expectation with the reality of what is feasible in terms of knowledge delivery by researchers. Scenario formulation can also be part of this process. Thus, to address Arctic climate change impacts on development pathways, one would identify and then merge derivatives of, for example, the AR5 RCP-SSP (van Vuuren et al., 2014; O'Neill et al., 2014) archive with new Arctic-specific socioeconomic specifications (Andrew 2014). In this scientist-policymaker arena, reduced complexity models (as discussed in Section 4.7) can be put to the test, enabling rapid, ensemble-based assessments of the impacts and unanticipated consequences of decisions: a major land use policy for Boreal forests, for instance, or establishing fishing quotas in a rapidly changing Arctic Ocean ecosystem.

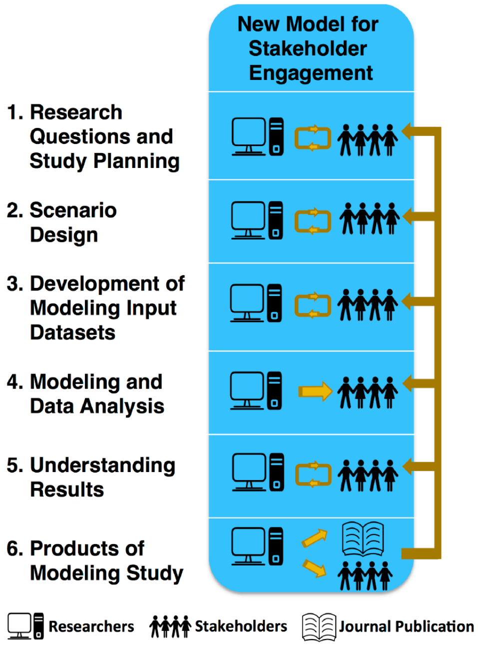
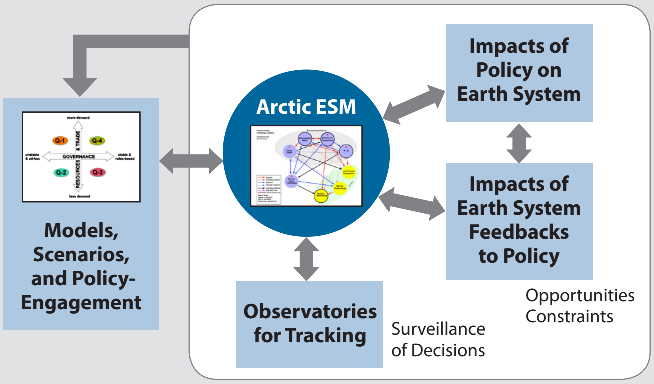


Figure 5.1. An example of a co-design process through which information consumers (stakeholders) interact directly with knowledge providers (scientists) to iteratively increase the relevancy of research products in the policy and management domains. From Rosenzweig et al. (2014); reprinted with permission, American Geophysical Union.

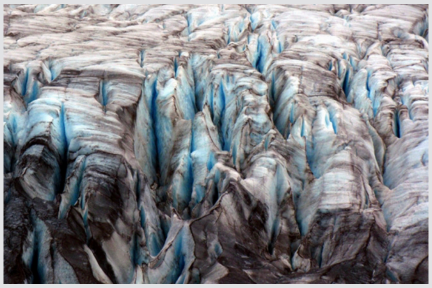
In the context of systems-informed policy formulation, science diplomacy takes on an important role (Table 5.1) (Berkman et al., 2017). It is an holistic process that

Box 5.1. Framing Systems Analysis in a Policy-Relevant Context

A co-design process to unite Arctic systems researchers with decision-makers has as one of its express aims the identification and evaluation of options for action, executed iteratively in order to accommodate the changing state of knowledge that inherently is produced through such a collaboration (Figure 5.1). In the case of black carbon, this co-design process would generate a series of plausible scenarios, specifying contrasting levels of emission reductions, their inherent economic costs, and the geographic limitation of emission sources. These scenarios would be appropriately cast at the pan-Arctic system scale in order to capture the essential interactions with pollutant emissions in the lower latitudes as well as the major atmospheric circulation patterns in the Arctic once the pollutants are introduced into the region. As this scenario space is defined, the simulations are parameterized and then executed to produce outputs that evaluate (a) the impact of a particular decision scenario on the Arctic and broader Earth system and (b) feedbacks onto the decision space itself, as the success or failure of particular control scenarios are revealed, for example, positive economic or investment benefits/constraints. An important byproduct of this framing is an articulation of key observations that would be necessary to trace and then verify the impact of the scenario, helping to guide the design of observatory networks (e.g., SAON, 2008; AMAP, 2012; AON DITF, 2012).



A decision-making framework combining Arctic Earth system modeling (ESM) with a co-design process for formulating and testing scenarios involving major human decisions. From IIASA: Arctic Futures Initiative.

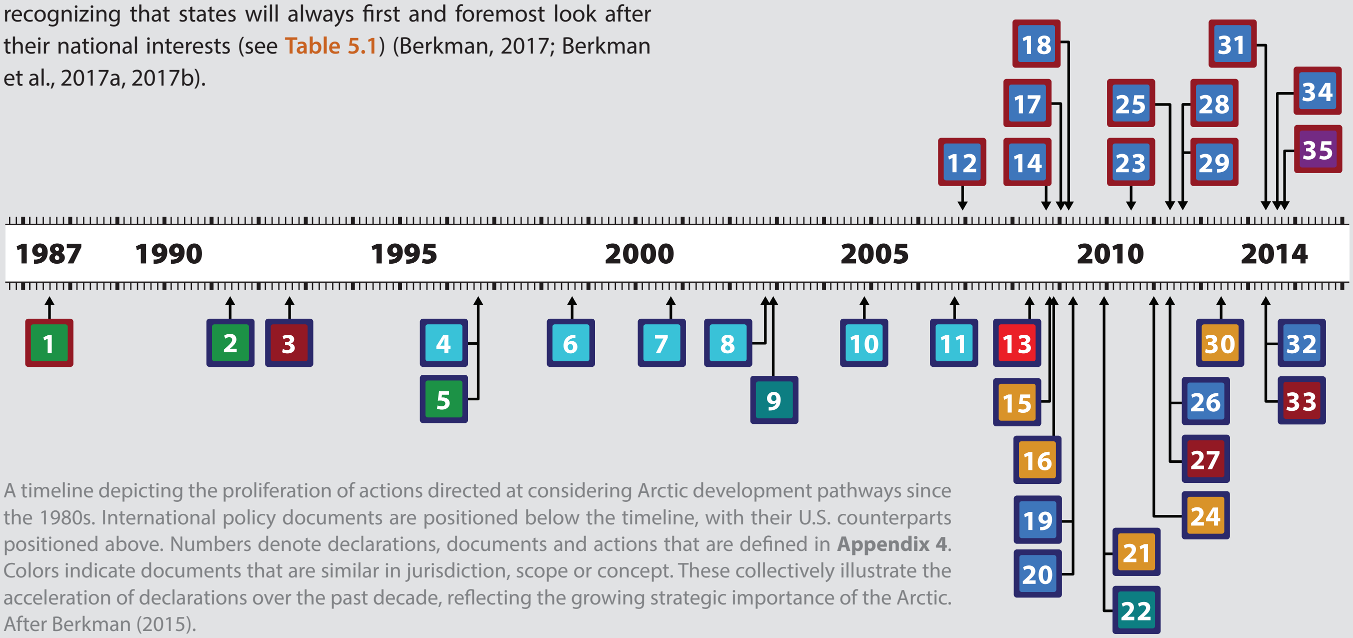


contributes to informed decision-making to balance national and international interests. In practice, science diplomacy and the decision-support process are one and the same, revealing a policy architecture to put sustainable development in the Arctic into operation for the benefit of society writ large. Integrated with data, governance records define the evidence that ultimately can be crafted into options to inform decisions. Consider, for example, application of the 1982 UN Convention on the Law of the Sea and the Agreement on Enhancing International Arctic Scientific Cooperation (Arctic Science Agreement; Berkman et al., 2017a) that must consider data about decreasing sea ice and increasing ship traffic in the Arctic Ocean. To address change in the Arctic Ocean, it is necessary to recognize that options involve the combination of fixed, mobile, and other built assets that require capitalization and technology (including communications, research, observing and information systems) *plus* regulatory, policy, and other governance mechanisms (including insurance). Informed decision-making involves built assets and governance mechanisms, which are both required for sustainable infrastructure development to achieve Arctic sustainability. Box 5.2 explores some of the mechanisms by which these aspirations may be realized.

Box 5.2. Arctic Systems Research and Science Diplomacy

In the international context of the Arctic, especially in the Arctic Ocean where questions extend across and beyond national jurisdictions with increasing frequency, diverse perspectives are nearly always involved. The system state-change in the Arctic Ocean is creating immediate economic opportunities along with ecosystem risks, where "eco" is taken to be the home for all in the Arctic. The innovation required is to balance economic prosperity, ecological protection and societal well-being. These three pillars of sustainability further involve stability, balancing urgencies of the moment and consideration of future generations. Consequently, options for informed decisions must operate across a continuum of urgencies from immediate security timescales to sustainability over multiple generations. It is important also to recognize that before national interests and common interests can be balanced—it first is necessary to build common interests, which is the primary contribution of *science diplomacy*, recognizing that states will always first and foremost look after their national interests (see Table 5.1) (Berkman, 2017; Berkman et al., 2017a, 2017b).

With $1 trillion in investment anticipated over the next couple of decades, progress to implement sustainable infrastructure development in the Arctic is demonstrated by the emergency-response agreements signed by the eight Arctic states in conjunction with the Arctic Council Ministerial Meetings: 2011 *Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the* Arctic; and 2013 *Agreement on Cooperation on Marine Oil Pollution, Preparedness and Response in the Arctic*. Creation of the Arctic Economic Council in 2013 as well as the Arctic Coast Guard Forum and Arctic Offshore Regulators Forum in 2015—which now rotate with Arctic Council chairmanships— is further evidence of a responsive policy agenda. The *Agreement on Enhancing International Arctic Scientific Cooperation and International Code for Ships Operating in Polar Waters (Polar Code)* that came into force on 1 January 2017 further reveals tangible steps to achieve Arctic sustainability.



A timeline depicting the proliferation of actions directed at considering Arctic development pathways since the 1980s. International policy documents are positioned below the timeline, with their U.S. counterparts positioned above. Numbers denote declarations, documents and actions that are defined in **Appendix 4**. Colors indicate documents that are similar in jurisdiction, scope or concept. These collectively illustrate the acceleration of declarations over the past decade, reflecting the growing strategic importance of the Arctic. After Berkman (2015).

CHAPTER 6.
PROGRAMMATIC NEEDS

The scientific issues and policy challenges articulated throughout this report are highly intertwined, richly interdisciplinary, and larger than the capacity of any small project or project team to fully advance. Similar challenges have been met through implementation of *team science* organized through a *collaboratory* (Cooke and Hilton, 2015): a meeting ground for trans-disciplinary research and policy engagement intended to produce holistic, systems-level understanding. Such centers have been highly successful in terms of their scientific impact, applications to societal needs, engagement of policymakers' return on research investment, and stimulating collaborations (CUAHSI, 2004; Carpenter et al., 2009; Hampton and Parker, 2011; Baron et al., 2017). They have recently been proposed as essential research infrastructure (Baron et al., 2017). We recommend the establishment of an Arctic Systems Collaboratory, while making note that the nature of such a center could take many forms (Bos et al., 2007).

Several unifying "currencies" as well as a working definition of what constitutes the Arctic system have been presented in this report. The issue of extremes was explored from the perspective of systems-level thinking and the narrative offered several examples of approaches to systems understanding and synthesis. Collectively, the report chapters lay out a research challenge and can be used to make the case that a systems-oriented approach will be needed to appropriately synthesize the evolving body of basic research in order to better understand the full dimensionality of Arctic change. Synthesis will also be necessary to provide policy-informing knowledge that can ultimately be used to support decisions seeking to respond to Arctic system change and its many derivative impacts.

In this chapter we address some programmatic requirements to build the human and technical infrastructure to move Arctic systems science forward. We pose the question: *What is necessary to design and implement an Arctic-focused synthesis center capable of assembling systemic views on what otherwise would be studied as disparate individual phenomena, key state variables, and their dynamics?* We outline the actions, personnel investments and organizational structures, as well as practical administrative and community-building efforts needed to create a collaborative research environment dedicated to forwarding systems-level perspectives. Given the broad and cross-cutting nature of the research challenge at hand an Arctic Systems Collaboratory will require ongoing input from a large number individuals and institutions (Adams et al. 2005), and thus be designed to evolve with the emerging science and stakeholder needs. Thus, a supportive structure must involve engagement from a broad community of Arctic researchers, combined with a sufficient, yet minimally centralized coordination to assure progress is as rapid and efficient as possible. Figure 6.1 provides an outline of the key design considerations discussed in the next sub-chapters.

6.1 Design Criteria for Successful Community Collaborations

The thinking here builds upon the work of the *Arctic System Science Committee* (*ARCSS*), which was active between 2004 and 2010 (ARCUS, 2010), when it was merged with activities of the *Study of Environmental Arctic Change* (*SEARCH*) program. It also draws from experience from the nearly contemporaneous *FreshWater Integration Study* (*FWI*; Arctic CHAMP, 2014; Vörösmarty et al., 2008). Through a series of meetings and workshops (e.g., see ARCUS, 2007a), *ARCSS* articulated consensus thinking from the Arctic research community of the time. It highlighted key features of a successful synthesis effort, including the importance of community science planning (such as the current effort), openness, transparency, and the empowerment of subcommunities. *ARCSS* also recommended four factors for success in such large-scale collaboratories:

- Clear integrating goals;
- Long-term funding (of at least five years);
- Sufficient opportunities for funded PIs and other participants to meet and exchange knowledge, virtually or in face-to-face meeting grounds; and
- Skilled administrative support for any emerging systems-level initiatives.

These remain important factors. In addition, a collaboratory should be designed to facilitate knowledge integration across disciplines. Integration needs to be viewed as an active process, entraining potentially large numbers of teams funded separately and working on their individual aspects of a problem. Integration is accelerated through repeated and substantive dialogue that exchanges data, formulates hypotheses, analyzes models and interprets the emerging results. These conversations require facilitation by leaders who understand the Arctic as a system, which in this context means at regional-to-globally relevant spatial scales and over time frames relevant to understanding the major forces at work behind climatic, ecosystem, and societal change. In a field as complex as Arctic system synthesis, the necessity of direct interaction and appropriate leadership and guidance of the dialogue process is clear.

To achieve creative and innovative research within the context of shared understanding and common data standards, a balance should be struck between advancing a common agenda yet enabling a sufficient degree of autonomy among the participating teams. Determining the appropriate level of coordination has to be assessed by the Collaboratory leadership on an ongoing basis. There is a natural, and we believe healthy, tension that needs to be cultivated among researchers studying at large versus small scales, those using inductive (observation-based) versus deductive (modeling) approaches, disciplinary versus cross-disciplinary methods, and basic versus applied research. We believe that a precise definition of the thematic boundaries of a synthesis center is not possible in advance and must be formulated in the context of specific proposals and work packages. However, it is anticipated that any support personnel working at such a Collaboratory engage individual research teams to ensure that projects contribute substantially to the broader vision of integrative, long-term, large-scale, and interdisciplinary studies of the evolution of the Arctic System and its most important subsystems. On a practical level, this requires human infrastructure to support communications, coordination, and collaboration (Bennett and Gadlin, 2012).

6.2. Challenges Intrinsic to Collaborative Research Teams

While intuitive in principle, in practice, there are many challenges to overcome in executing collaboration across disciplines, institutions, nations and sectors. These involve: issues

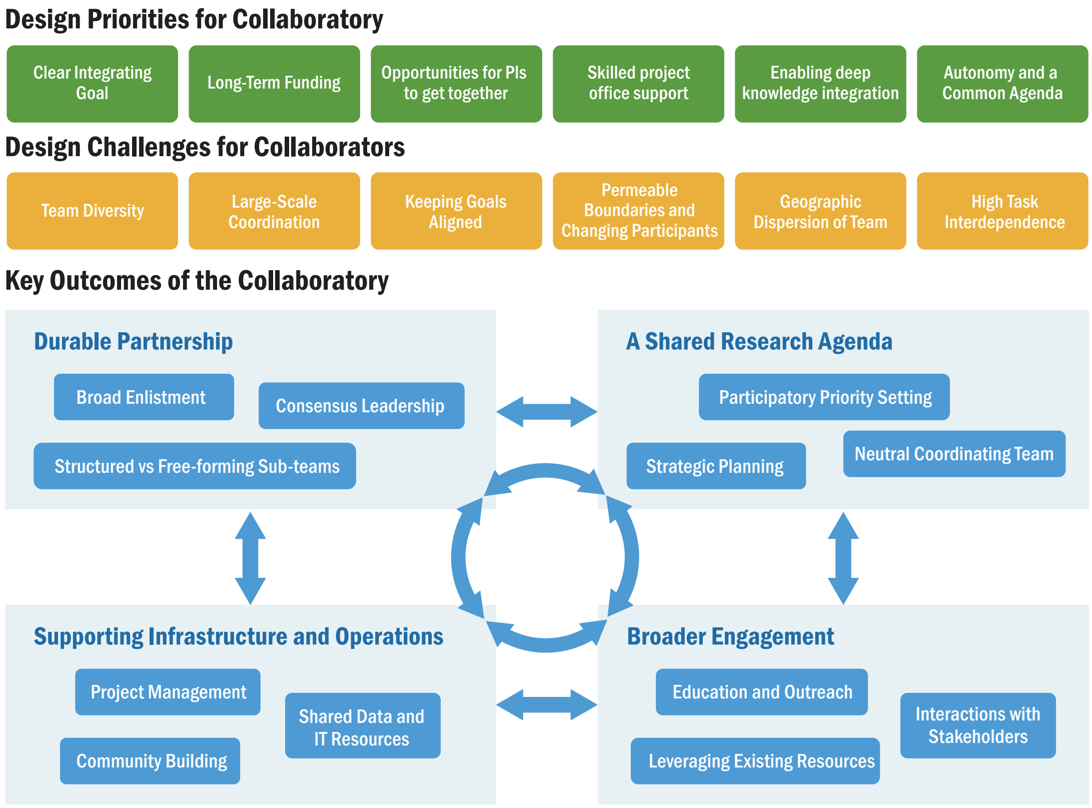


Figure 6.1. Core design elements of a successful community-based collaboratory for Arctic systems research synthesis.

of inclusivity; providing a shared sense-of-purpose; preventing the goals and objectives from proliferating or running aground; overcoming the realities of multi-institutional and potentially multi-national collaborations; and, containing the propensity of individual research agendas to fragment the broader, shared research vision. These are discussed immediately below. In the experience of the organizing committee and workshop participants we find that these potential obstacles can be overcome by an appropriate structuring of the collaboratory structure, its management and operations.

Team Diversity and Inclusion

Diversity presents challenges in a very practical sense, as collaborating, interdisciplinary partners typically lack a shared vocabulary, scale perspectives and values, and may originate from completely different knowledge systems (e.g., Indigenous knowledge and Western science; or biological vs physical sciences) (Vörösmarty et al., 2010). However, engagement across disciplines and with all stakeholder communities is necessary to afford successful systems research. And, the sooner participants achieve knowledge integration, common languages, shared approaches and mutual respect for their differences, the more efficient will be the research in the long run. As shown in Figures 1.1 and 1.3, there is surprising common ground already in place in the arena of systems-level thinking about the Arctic.

Large-Scale Coordination

Given the breadth of the basic and applied research challenges of Arctic system synthesis, it is plausible that participants in this collaborative enterprise could potentially number in the hundreds, if not thousands, when researchers at all career levels, from all parts of the world, and all cultural and linguistic backgrounds—including Indigenous populations—are considered. Dedicated systems for communication and coordination will be needed to support coherent progress. At a technical level, this requires the use of intranet-type online platforms, intra-project messaging, and universally used file storage platforms. At a human level, it will require community-building from the bottom up yet also adaptive management strategies from above. Thus, a balance must be sought between the "chaos of ideas," which is necessary to ensure creative breeding grounds for the best research, and a sufficient level of order to manage the chaos and keep participants dedicated to the enterprise at hand—systems synthesis.

Keeping Goals Aligned

Research groups working within the partnership may have diverse, sometimes incompatible objectives. These differences can be accommodated, at least in part, through an appropriate governance framework to ensure broad participation in decision-making. Clear statements of overarching project goals and objectives, mutually agreed upon at project initiation and rigorously followed, should be in place in order to keep goals aligned. When changes need to be made in a project's overall objectives, as often happens in research, there must be clear procedures to ensure community acceptance (Adams et al., 2005).

Permeable Boundaries and Changing Participants

With large, distributed teams such as those envisioned in this collaboratory, participants will be cycling into and out of the work frequently. The natural career progression of students through different levels of their training and into employment adds to these challenges, as does the shifting focus of the research agenda, which will require new skills and expertise. The center's structure must be flexible and adaptable enough to accommodate the expected high turnover rates of human capital. A mechanism to actively archive and access a "corporate history" must be in place to create a legacy of research, which in turn is passed on to subsequent generations of participants.

Geographic Dispersion of the Team

Arctic researchers' home organizations cut across institutional, national and other geographic boundaries. Field sites and periods of field work span the entire extended Arctic and all seasons. Thus, tools such as a robust shared calendar, the ability to support and facilitate frequent virtual meetings, and shared project cloud files will be needed.

High Task Interdependence

Operating on a systems level will create an unusual number of dependencies between the work conducted by multiple researchers and research teams. In order to avoid unmet dependencies from derailing another group's work, pragmatic procedures need to be in place to coordinate across groups on a regular basis. This requires a suitable oversight by an advisory board (or its equivalent), facilitated by technology support that includes group calendaring, sharing of project and logistical plans, frequent virtual check-ins, etc.

6.3. Key Outcomes Targeted by the Collaboratory

With the design criteria and key challenges to a successful collaboratory in mind from the preceding sub-chapters, an operational vision of the Arctic Systems Collaboratory can be formulated around a set of clear and achievable outcomes. We propose twelve specific outcomes, which are discussed immediately below, grouped into the four major core design elements presented in Figure 6.1.

A Durable Partnership

Broad Recruitment of the Community. In order to be representative of the most timely developments yielded by the broader Arctic research community and to leverage the collective wisdom of a wide range of scientists and policymakers, it is imperative that opportunities regularly be made available for any researcher or stakeholder to: contribute their perspectives on the focus of the project at hand; contribute their insights and creativity to the challenges which are being addressed; have a voice in the approaches to be taken, products to be produced, and application of the resources provided to the collaborator. Regular communiqués to the community through electronic newsletters and web postings, together with participant response outlets, like webinars, physical meetings, and collaborative digital workspaces are envisioned in order to achieve and sustain an appropriate level of participation.

Structured and Free-Forming Project Sub-Teams. Some systems-level questions bear intrinsic research infrastructure requirements. For example, the critical lack of time series observations of the key currencies described in Chapter 2, necessitating data archiving and discovery tools. To provide such a "fundamental", there needs to be coherency of purpose through long-term commitments to design, implement, harmonize and provide data in a sufficiently reliable manner that enables change detection, uncovering of system interconnections and validation of systems analysis models. Such efforts require a well-defined, if not rigid, structure to ensure continuity and reliability in the data provision. On the other hand, some important questions will certainly emerge organically from ongoing research and will require flexibility in order to form and re-form research teams. Thus, both fixed and free-forming organizations need to have a place within the coordinating umbrella of the collaboratory.

Consensus Leadership Team. To play its role in setting community-wide research priorities, the collaboratory must be scrupulously unbiased and open to wide-ranging participation and leadership (Cooke and Hilton, 2015). Both large and small-scale institutions, Arctic Indigenous residents and representatives, funding agencies, private industry, governmental staff, and other stakeholders should all be able to find a seat at the leadership table. Approaches such as open workshops, appreciative inquiry (Bush, 2013), and community-driven scenario thinking exercises can help to make sure that all voices are heard and respected.

A Shared Research Agenda

Participatory Priority-Setting. Building upon the synthesis plan described in this report, it will be necessary to keep a focus on cooperatively developed, mutually agreed upon priorities among the many interested researchers, various stakeholder groups, and funders. Especially in research relating to the socio-environmental systems in the Arctic, it is imperative to co-design projects reflecting the perspectives of scientists, Arctic residents and policymakers who are charged with resource and environmental management, and others who can be affected both by the research itself and its findings. Planning that reflects multi-stakeholder priorities, Indigenous and traditional knowledge, and co-production of a study agenda crafted by researchers and residents holds great promise for meeting the needs of those affected (Raymond-Yakoubian and Raymond-Yakoubian, 2017). The proposed collaboratory should include ample opportunity for workshops, community meetings, and stakeholder roundtables to support positive outcomes.

Strategic Planning. The scientific and administrative leadership, working with external stakeholders, will need to set priority objectives and create implementable plans. Regular review and course corrections should take place at least annually. As the research effort proceeds and knowledge advances, new calls will likely emerge for more detailed studies. Prioritization among these opportunities can take many forms (e.g., peer review panels evaluating competitive proposals, discretionary awards by project leaders), but without a consistent set of guiding principles it could quickly devolve to a chaotic collection of unrelated projects that fail to reflect the aspirations of Arctic system synthesis research (see Swanberg and Holmes, 2013). Ideally, this set of priorities could be developed bottom-up by a participatory community process.

Neutral Coordinating Team. Research-active academic partners should comprise the core of the collaboratory team in an alliance with experts from industry, government, NGOs, Indigenous knowledge holders, and others. Arguably, coordination and responsibility of the collaboratory would benefit from some level of centralization. Examples exist from the National Labs (e.g., UCAR; Sandia National Labs managed by Honeywell; Brookhaven National Lab managed by SUNY). The National Center for Ecological Analysis and Synthesis is managed by the University of California, and has been a successful model of collaboration across the environmental sciences and community. A neutral and unbiased advisory board that represents a cross section of Arctic researchers broadly could help to ensure that center coordination at the scientific and programmatic levels is fair and unbiased.

Supporting Infrastructure and Operations

Appropriately Centralized Project Management. In order to set and accomplish a collaboratory's shared objectives, to meet timelines, and to coordinate across the many interconnected research projects, a centrally based project management capacity would be required. On the operational level, a skilled team with deep relationships across the broad human landscape of the Arctic could be charged with overall project support, meeting coordination, use of communications technology, and consensus building. Coordination with appropriate technical organizations, including transport and field logistics will also be a focus of this centralized management.

Community-Building within the Collaboratory. Often, the most profound discoveries occur when researchers from very different fields engage in dialogue around a common research problem (e.g., Convergence research; Box 1.5). To facilitate these interactions, the synthesis center should organize and make available a wide variety of venues for cross-boundary collaboration. This will likely include in-person workshops and meetings, virtual conferences, videoconference meetings, online discussion fora, email lists, and social media groups/pages to allow for a range of synchronous and asynchronous discussions at varying levels of engagement.

Shared Data and IT Resources. As argued earlier in this document, systems-level science will be facilitated by the capacity of teams to interact and exchange knowledge with relative ease. In the digital age, the need to inter-compare and merge disparate digital data sets is apparent. Therefore, one of the essential ingredients for Arctic systems analysis will be a coordinated, shared repository for data, which could sensibly be linked to existing NSF (ACADIS) and other Arctic research data infrastructure investments, for example from NASA, NOAA and USGS. Stringent data quality and metadata standards will be essential. Those generating data as part of the collaboratory will need to deposit such data, provide useful metadata tagging, documentation, and meet QA/QC (quality assurance/quality control) standards. Researchers need to be actively encouraged to leverage the data collected by others, and data re-use should be a metric of program success.

Broader Engagement

Education and Outreach. The center also should have a digital, public presence through integrated web, social media, email, and database portals, providing access to the project's participants, events, studies, data sets, and outreach products. This makes the results of the collaboratory useful to non-technical stakeholders, and helps to create an informed citizenry about ongoing changes across the Arctic and how systems-level research can contribute to societally driven information needs. While this is conceptually simple this has, in practice, proven difficult to achieve. Skilled educators should be engaged in making sure that the necessary translation and communication of results occurs. The center should make its organizational and technical infrastructure, including pedagogical consultation, available to researchers interested in improving the outreach aspects of their work.

Leveraging Existing Resources. There are numerous academic organizations, NGOs, government agencies, and scientific alliances that have had a long-standing interest in Arctic research. Every effort should be made to capitalize on these capabilities, that is, to identify the essential, existing body of Arctic systems-relevant science. The objective is to avoid duplication of existing activities and roles where other organizations are effective at advancing Arctic-relevant knowledge. By entraining into a systems collaboratory distinguished members of the research community and its stakeholders, and with the coordination of long-standing Arctic "connecting" organizations, such duplication can be avoided. A collaborative community activity like this should be designed to be opportunistic, filling unmet needs and working in concert with all existing efforts.

Interactions with Stakeholders. While the focus of the collaboratory envisioned here is intended to be the advancement of fundamental Arctic system knowledge, the goals and objectives must take into account the needs of all stakeholders and decision-makers. Mechanisms should be in place from the collaboratory's inception to allow the research agenda to be shaped by consultation with these voices. Practical steps, like the scenario co-design process discussed in Chapter 5 and Box 5.1, will help to achieve this societally relevant outcome.

APPENDIX 1.

PARTICIPANTS AND CONTRIBUTORS

ORGANIZING AND DRAFTING COMMITTEE MEMBERS

Dr. Charles J. Vörösmarty
Director, Environmental Sciences Initiative
Advanced Science Research Center
Graduate Center of the City University of New York (CUNY)
and
Professor of Civil Engineering
The City College of New York
Email: charles.vorosmarty@asrc.cuny.edu

Dr. Michael Rawlins
Associate Director, Climate System Research Center
University of Massachusetts-Amherst
Email: rawlins@geo.umass.edu

Dr. Larry Hinzman
Vice Chancellor for Research
University of Alaska Fairbanks
Email: ldhinzman@alaska.edu

Dr. Jennifer Francis
Research Professor
Department of Marine and Coastal Sciences
Rutgers University
Email: francis@imcs.rutgers.edu

Dr. Mark Serreze
Director, National Snow and Ice Data Center
University of Colorado, Boulder
Email: serreze@nsidc.org

Dr. Anna Liljedahl
Research Director
Water and Environmental Research Center
University of Alaska, Fairbanks
Email: akliljedahl@alaska.edu

Dr. Kyle McDonald
Chair, Earth and Atmospheric Science
City College of New York, CUNY
Email: kmcdonald2@ccny.cuny.edu

Dr. Michael Piasecki
Associate Professor of Civil Engineering
City College of New York (CUNY)
Email: mpiasecki@ccny.cuny.edu

Dr. Robert Rich
Executive Director
Arctic Research Consortium of the United States (ARCUS)
Email: bob@arcus.org

WORKSHOP SPEAKERS AND ATTENDEES

Dr. Paul Berkman
Professor of Practice in Science Diplomacy
The Fletcher School
Tufts University

Peter Bieniek
Research Assistant Professor
International Arctic Research Center
University of Alaska, Fairbanks

Dr. Karim Chichakly
Co-President
Isee systems, Inc.
Lebanon, NH

Mr. Alexander Crawford
Graduate Student
University of Colorado, Boulder

Dr. Richard Cullather
Research Associate
NASA-Goddard Space Flight Center
University of Maryland

Dr. Matthew Druckenmiller
Research Scientist
National Snow and Ice Data Center
University of Colorado, Boulder
and
Research Associate
Department of Marine and Coastal Sciences
Rutgers University

Hajo Eicken
Director
International Arctic Research Center
University of Alaska Fairbanks, Alaska

Dr. Scott Goetz
Professor
School of Informatics, Computing and Cyber Systems
Northern Arizona University

Dr. Janet Intreieri
Research Scientist
Polar Observations and Processes Team
NOAA Earth System Research Laboratory (Boulder Colorado)

Dr. Elchin Jafarov
Research Associate
Computational Earth Sciences
Los Alamos National Laboratory

Dr. Miriam Jones
Research Geologist
Eastern Geology and Paleoclimate Science Center
U.S. Geological Survey, Reston

Dr. Glenn Juday
Professor of Forest Ecology
International Arctic Research Center
University of Alaska, Fairbanks

Dr. Brendan Kelly
Director, Conservation Research and Chief Scientist
Monterey Bay Aquarium
and
Executive Director
Study of Environmental Arctic Change
International Arctic Research Center
University of Alaska Fairbanks

Dr. Lyudmila Lebedeva
Junior Research Scientist
Laboratory of Permafrost Groundwater and
Geochemistry Melnikov Permafrost Institute Yakutsk (RUSSIA)

Dr. Jim McClelland
Associate Professor
Marine Science Institute
University of Texas, Austin

Dr. Charles Miller
Principal Investigator
Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)
Jet Propulsion Laboratory

Dr. Maribeth Murray
Executive Director
Arctic Institute of North America
University of Calgary

Dr. Susan Natali
Associate Scientist
Woods Hole Research Center
Woods Hole, Massachusetts

Dr. Bob Newton
Research Scientist
Lamont-Doherty Earth Observatory
Columbia University

Dr. Tad Pfeffer
Fellow
INSTAAR
University of Colorado, Boulder

Dr. Stephanie Pfirman
Professor
Lamont-Doherty Earth Observatory
Columbia University

Dr. Anni Reissell
Science Coordinator
University of Helsinki (FINLAND)
and
Guest Research Scholar
International Institute of Applied Systems Analysis (IIASA) (AUSTRIA)

Dr. Asa Rennermalm
Associate Professor of Geography
Rutgers University

Dr. Elena Rovenskaya
Program Director
Advanced Systems Analysis Program
International Institute for Applied Systems Analysis (IIASA) (AUSTRIA)

Ms. Caitlin Rushlow
Graduate Student
Idaho State University

Dr. Christina Schädel
Assistant Research Professor
Center for Ecosystems Sciences and Society
Northern Arizona University

Dr. Michael Steele
Senior Principal Oceanographer
Polar Science Center
Applied Physics Laboratory
University of Washington

Dr. Nicholas Steiner
Postdoctoral Researcher
The City College of New York

APPENDIX 2

The November 2016 Workshop Agenda

NSF-ARCSS Sponsored Community Workshops for Synthesis Studies of the Pan-Arctic/Earth System

WORKSHOP 1: EXTREME EVENTS IN CONTEMPORARY AND FUTURE TIMEFRAMES

Environmental CrossRoads Initiative, Advanced Science Research Center (ASRC)
The City University of New York, New York, NY (USA)
14-16 November 2016

Framing Question: *What are the biogeophysical forces that generate extreme events in the Arctic, how do they function, how do these change over time and thus emerge in the future?*

MONDAY, 14 NOVEMBER

8:30 AM – 9:30 AM	Welcome, Introductions Workshop Goals Overview of Day 1
9:30 AM – 10:30 AM	PUTTING IT ALL TOGETHER: THE ARCTIC SYSTEM ***Larry Hinzman****, Vice Chancellor for Research, University of Alaska Fairbanks* Panel Discussion: Organizing Committee
10:30AM – 10:45 AM	BREAK
10:45 AM – 11:45 AM	APPROACHES TO SYNTHESIS ON TREATING EXTREMES ***Charles Vörösmarty****, Director, Environmental CrossRoads Initiative, City University of New York, NY* Panel Discussion: Organizing Committee
11:45 AM – 12:45 PM	LUNCH (catered)
OVERVIEW TALKS:	*presenting the issue of extreme events from the perspectives of the disciplinary domain listed* (Each: 15 minutes)

ARCTIC ATMOSPHERE AND CLIMATE

12:45 PM – 1:00 PM	PAN-ARCTIC CLIMATOLOGY ***Mark Serreze****, Director, National Snow and Ice Data Center, University of Colorado, Boulder*
1:00 PM – 1:15 PM	WEATHER FORECASTING AND NOAA WEATHER RESEARCH ***Janet Intreieri,*** *Research Scientist, Polar Observations and Processes Team, Earth System Research Laboratory, NOAA*
1:15 PM – 1:30 PM	WEATHER ***Alexander Crawford****, Graduate Student, University of Colorado, Boulder*
1:30 PM – 1:45 PM	ATMOSPHERIC DYNAMICS AND TELECONNECTIONS BETWEEN THE ARCTIC AND LOWER LATITUDES ***Jennifer Francis****, Research Professor at the Institute of Marine and Coastal Sciences at Rutgers University*
1:45 PM – 2:00 PM	BREAK

ARCTIC OCEAN

2:00 PM – 2:15 PM	SEA ICE OBSERVATIONS ***Hajo Eicken****, Director, International Arctic Research Center, University of Alaska Fairbanks, Alaska*
2:15 PM – 2:30 PM	NUTRIENT CYCLING AND OCEAN BIOGEOCHEMISTRY ***Bob Newton,*** *Research Scientists, Lamont-Doherty Earth Observatory, Columbia University*
2:30 PM – 2:45 PM	TERRESTRIAL ARCTIC: FRESHWATER-OCEAN LINKAGES ***Asa Rennermalm****, Geography Department, Rutgers University, New Brunswick, New Jersey*
2:45 PM – 3:00 PM	BREAK

TERRESTRIAL ARCTIC HYDROLOGY

3:00 PM – 3:15 PM	HYDROCLIMATOLOGY ***Michael Rawlins****, Assistant Professor, University of Massachusetts, Amherst*
3:15 PM – 3:30 PM	PERMAFROST-HYDROLOGY LINKAGES ***Anna Liljedahl****, Research Director, Water and Environmental Research Center, University of Alaska Fairbanks*
3:30 AM – 3:45 PM	PERMAFROST-ECOLOGY-CARBON LINKAGES ***Susan Natali****, Associate Scientist, Woods Hole Research Center, Woods Hole, Massachusetts*
3:45 PM – 4:00 PM	MONITORING ARCTIC FREEZE-THAW DYNAMICS ***Kyle McDonald****, Professor, Earth and Atmospheric Science Department, The City College of New York, New York, NY*
4:00 PM – 5:00 PM	PLENARY QUESTIONS and DISCUSSION
5:00 PM – 5:15 PM	RECAP OF DAY/RECALIBRATION
5:15 PM	ADJOURN FOR DAY
5:15PM – 5:45 PM	COMMITTEE MEETING TO DISCUSS BREAK OUT GROUPS
7:00 PM	DINNER AT CARMINE'S

TUESDAY, 15 NOVEMBER

9:00 AM – 9:20 AM	Overview of Day 2

TERRESTRIAL ECOSYSTEMS AND POLLUTANTS

9:20 AM – 9:35 AM	FIRES ***Glenn Juday****, International Arctic Research Center, University of Alaska Fairbanks, Alaska*
9:35 AM – 9:50 AM	IMPACTS OF SEA ICE LOSS ***Brendan Kelly****, Executive Director, Study of Environmental Arctic Change, International Arctic Research Center, University of Alaska Fairbanks*
9:50 AM – 10:05 AM	ARCTIC POLLUTANTS ***Stephanie Pfirman****, Professor, Lamont-Doherty Earth Observatory, Columbia University, New York, NY*
10:05 AM – 10:20 AM	BREAK

ARCTIC STAKEHOLDERS

10:20 AM – 10:35 AM	SOCIAL SYSTEM RESPONSES TO ENVIRONMENTAL EXTREMES ***Maribeth Murray****, Executive Director, Arctic Institute of North America, University of Calgary, Calgary, Canada*
10:35 AM – 10:50 AM	INFORMED POLICIES TO ADDRESS FUTURE EXTREMES ***Anni Reissell****, Science Coordinator, University of Helsinki, Finland and Guest Research Scholar, International Institute of Applied Systems Analysis, Laxenberg, Austria*

10:50 AM – 11:05 AM	U.S. PERSPECTIVES ON POLICYMAKING ***Brendan Kelly****, Former Assistant Director for Polar Science in the Office of Science and Technology Policy (OSTP), Executive Office of the President of the United States*
11:05 AM – 11:20 AM	BREAK

INFORMATICS AND BIG CAMPAIGNS

11:20 AM – 11:35 AM	INTEGRATED OBSERVATION CAMPAIGNS ***Charles Miller,*** *Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), Jet Propulsion Laboratory*
11:35 AM – 11:50 AM	ARCTIC STAKEHOLDERS: INFORMATICS AND RESEARCH ***Michael Piasecki****, Associate Professor, Dept. of Civil Engineering, The City University of New York, NY*
12:00 PM – 1:00 PM	LUNCH (catered)
1:00 PM – 2:30 PM	Plenary and Open Discussion Charge to Breakout Groups
2:30 PM – 5:15 PM	BREAKOUT GROUPS (Session #1)
5:15 PM – 5:45 PM	REPORTS BACK FROM BREAKOUT GROUPS (Session #1)
5:45 PM – 6:00 PM	RECAP OF DAY/RECALIBRATION
6:00 PM	ADJOURN FOR DAY
	DINNER ON OWN

WEDNESDAY, 16 NOVEMBER

8:30 AM – 8:45 AM	Overview of Day 3 Charge to Breakout Groups
8:45 AM – 10:45 AM	BREAKOUT GROUPS (Session #2)
10:45 AM – 11:30 AM	REPORTS BACK FROM BREAKOUT GROUPS (Session #2)
11:30 AM – 11:45 AM	RECAP OF DAY AND WORKSHOP OVERALL
11:45 AM	CONCLUSION OF WORKSHOP

WEDNESDAY, 16 NOVEMBER (Drafting Committee Meeting)

12:00 PM – 5:00 PM	Drafting of conclusions and recommendations from workshop

APPENDIX 3
The April 2017 Workshop Agenda

NSF-ARCSS Sponsored Community Workshops for Synthesis Studies of the Pan-Arctic/Earth System

WORKSHOP 2: SYSTEM-LEVEL CURRENCIES (ENERGY, WATER, CARBON AND NUTRIENTS) AND THEIR ROLE IN AN EVOLVING ARCTIC

ARCUS (Arctic Research Consortium of the United States) Offices
1201 New York Avenue, Fourth Floor
Washington, DC (USA)
17-19 April 2017

Framing Question: *How are the key system-level currencies interlinked to form a unified and evolving Arctic system?*

MONDAY, 17 APRIL (Key Science Issues)

8:30 AM – 9:15 AM	Welcome (Bob Rich, ARCUS) Introductions Workshop Goals and Prospectus for Day 1(Charles Vörösmarty)
9:15 AM – 10:00 AM	APPROACHES TO SYNTHESIS ON CURRENCIES ***Charles Vörösmarty****, Director, Environmental Sciences Initiative, City University of New York, NY* ***Larry Hinzman****, Vice Chancellor for Research, University of Alaska, Fairbanks* Open Discussion/Q & A
10:00 AM – 10:15 AM	Break
OVERVIEW TALKS:	*briefly presenting the issue of currencies from the perspectives of each of the disciplinary domains listed*

CURRENCY: ENERGY

10:15 AM – 10:30 AM	PAN-ARCTIC ENERGY BUDGET ***Mark Serreze****, Director, National Snow and Ice Data Center, University of Colorado, Boulder (USA)*
10:30 AM – 10:45 AM	ENERGY AND SEA ICE ***Matthew Druckenmiller****, National Snow and Ice Data Center, U. of Colorado, Boulder (USA) and Department of Marine and Coastal Sciences, Rutgers University*
10:45 AM – 11:00 AM	ENERGY AND ATMOSPHERE ***Peter Bieniek****, International Arctic Research Center, University of Alaska, Fairbanks (USA)*
11:00 AM – 11:15 AM	ENERGY: ARCTIC-LOWER LATITUDE TELECONNECTIONS ***Richard Cullather,*** *NASA-Goddard Space Flight Center, University of Maryland (USA)*
11:15 AM – 11:30 AM	ENERGY, SOILS AND PERMAFROST ***Elchin Jafarov****, Computational Earth Sciences, Los Alamos National Laboratory, Los Alamos, NM (USA)*
11:30 AM – 12:00 PM	OPEN DISCUSSION
12:00 PM – 1:00 PM	LUNCH (catered)

CURRENCY: WATER

1:00 PM – 1:15 PM	ARCTIC OCEAN FRESHWATER ***Michael Steele**, Polar Science Center, University of Washington (USA)*
1:15 PM – 1:30 PM	TERRESTRIAL HYDROLOGY IN RUSSIA – AN OVERVIEW ***Lyudmila Lebedeva**, Melnikov Permafrost Institute, Yakutsk (RUSSIA)*
1:30 PM – 1:45 PM	HYDROLOGY: PERMAFROST, MOUNTAIN GLACIERS AND CLIMATE ***Anna Liljedahl**, Research Director, Water and Environmental Research Center, University of Alaska, Fairbanks (USA)*
1:45 PM – 2:00 PM	EXTREMES IN HYDROLOGY: FLOODING AND DROUGHT ***Michael Rawlins**, Climate System Research Center, University of Massachusetts, Amherst (USA)*
2:00 PM – 2:15 PM	GLACIERS AND ICE SHEETS: CHANGING WATER BALANCES ***Tad Pfeffer**, INSTAAR, University of Colorado, Boulder (USA)*
2:15 PM – 2:45 PM	OPEN DISCUSSION

CURRENCY: CARBON AND BIOGEOCHEMISTRY

2:45 PM – 3:00 PM	OCEAN BIOGEOCHEMISTRY (*beyond carbon)* ***Bob Newton**, Lamont-Doherty Lab, Columbia University, Palisades, NY (USA)*
3:00 PM – 3:15 PM	BREAK
3:15 PM – 3:30 PM	PERMAFROST-CARBON DYNAMICS ***Christina Schädel**, Center for Ecosystems Sciences and Society, Northern Arizona University, Flagstaff, AZ (USA)*
3:30 PM – 3:45 PM	RIVERINE FLUXES ***Jim McClelland**, Marine Science Institute, University of Texas, Austin (USA)*
3:45 PM – 4:15 PM	OPEN DISCUSSION

EXAMPLES OF STUDYING LINKED CURRENCIES

4:15 PM – 4:30 PM	ENERGY AND WATER IN THE PAN-ARCTIC ***Mark Serreze**, Director, National Snow and Ice Data Center, University of Colorado, Boulder (USA)*
4:30 PM – 4:45 PM	ENERGY AND WATER IN THE OCEAN COMPONENT OF THE PAN-ARCTIC ***Michael Steele**, Polar Science Center, University of Washington (USA)*
4:45 PM – 5:00 PM	MODELING AND SYNTHESIS OF WATER-CARBON FLUXES ***Michael Rawlins**, Climate System Research Center, University of Massachusetts, Amherst (USA)*
5:00 PM – 5:15 PM	OPEN DISCUSSION
5:15 PM – 5:45 PM	GENERAL DISCUSSION RECAP OF DAY/RECALIBRATION
5:45 PM – 6:00 PM	RECAP OF DAY/RECALIBRATION
6:00 PM	ADJOURN FOR DAY

TUESDAY, 18 APRIL (Broader Applications and Approaches to Linkages)

8:45 AM – 9:00 AM	Overview of Day 2

EXAMPLES OF STUDYING LINKED CURRENCIES CONTINUED

9:00 AM – 9:15 AM	ARCTIC PERMAFROST DYNAMICS: LINKS TO GAS EMISSION ***Miriam Jones**, Eastern Geology and Paleoclimate Science Center, U.S. Geological Survey, Reston, Virginia (USA)*

CURRENCIES TO SUPPORT POLICY AND APPLICATIONS

9:15 AM – 9:30 AM	IMPLICATIONS OF CURRENCY CHANGES ON ARCTIC BIODIVERSITY ***Glenn Juday**, School of Natural Resources and Extension, University of Alaska, Fairbanks (USA)*

9:30 AM – 9:45 AM	CURRENCIES AND ARCTIC SCIENCE DIPLOMACY ***Paul Berkman**, The Fletcher School at Tufts University, Medford MA (USA)*
9:45 AM – 10:00 AM	OPEN DISCUSSION

APPROACHES TO SYSTEMS-LEVEL SYNTHESIS

10:00 AM – 10:15 AM	POSSIBILITIES TO REMOTELY SENSE THE CURRENCIES ***Kyle McDonald**, Earth and Atmospheric Science, City College of New York, CUNY (USA)*
10:15 AM – 10:30 AM	REMOTE SENSING OF CARBON DYNAMICS ***Scott Goetz**,School of Informatics, Computing and Cyber Systems, Northern Arizona University, Flagstaff (USA)*
10:30 AM – 10:45 AM	BREAK
10:45 AM – 11:00 AM	CAPTURING DYNAMICS IN REDUCED COMPLEXITY MODELS ***Elena Rovenskaya**, Program Director, Advanced Systems Analysis Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg (Austria)*
11:00 AM – 11:15 AM	A PLATFORM FOR REDUCED SYSTEM MODELING ***Karim Chichakly**, Isee systems, inc., Lebanon NH (USA)*
11:15 AM – 11:45 AM	PUTTING IT ALL TOGETHER: THE ARCTIC SYSTEM ***Larry Hinzman**, Vice Chancellor for Research, University of Alaska, Fairbanks* Panel Discussion: Organizing Committee
11:45 AM – 12:15 PM	OPEN DISCUSSION
12:15 PM – 12:45 PM	LUNCH (catered)
12:45 PM – 1:45 PM	DISCUSS BREAKOUT TOPICS,CHARGE TO BREAKOUT GROUPS
1:45 PM – 3:30 PM	BREAKOUT GROUPS (Session #1)
3:30 PM – 3:45 PM	BREAK
3:45 PM – 5:00 PM	BREAKOUT GROUPS (Session #1 continued)
5:00 PM – 6:00 PM	REPORTS FROM BREAKOUT GROUPS w/ DISCUSSION (Session #1)
6:00 PM – 6:15 PM	RECAP OF DAY/RECALIBRATION
6:15 PM	ADJOURN FOR DAY

WEDNESDAY, 19 APRIL

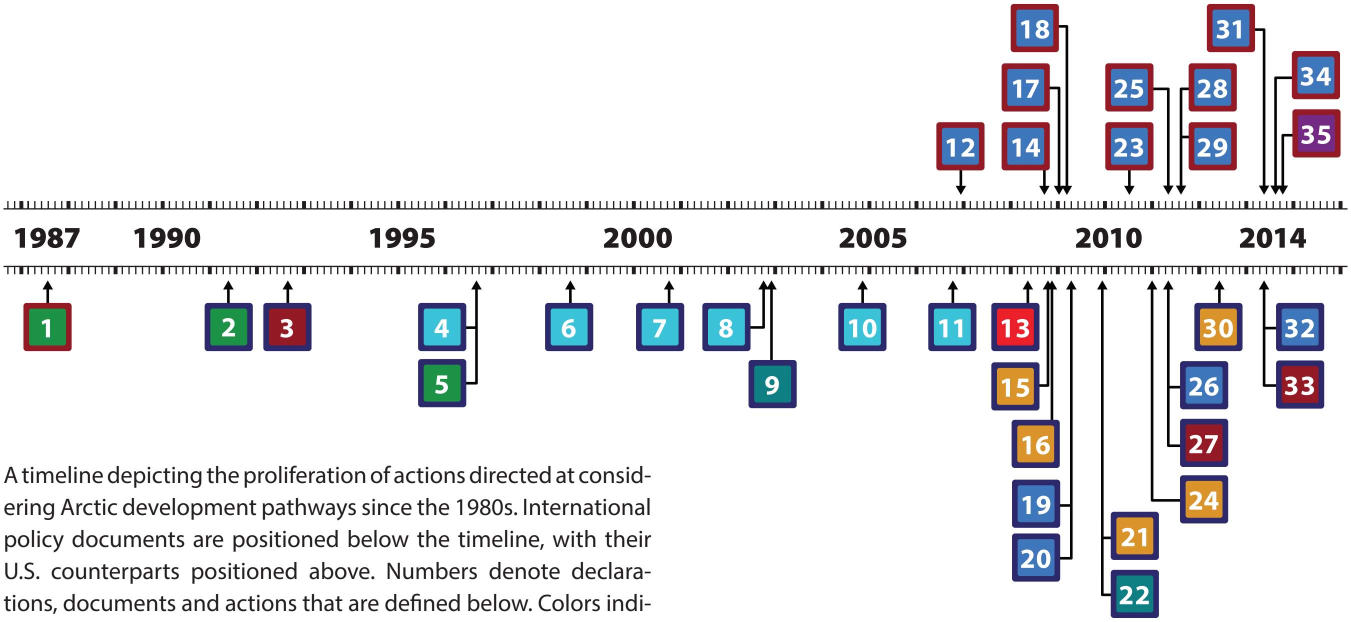
8:30 AM – 8:45 AM	OVERVIEW OF DAY 3
8:45 AM – 9:00 AM	DISCUSS BREAKOUT TOPICS AND CHARGE TO BREAKOUT GROUPS
9:00 AM – 10:30 AM	BREAKOUT GROUPS (Session #2)
10:30 AM – 10:45 AM	BREAK
10:45 AM – 11:45 AM	BREAKOUT GROUPS (Session #2 continued)
11:45 AM – 12:30 PM	REPORTS FROM BREAKOUT GROUPS w/ DISCUSSION (Session #2)
12:30 PM – 1:00 PM	OPEN DISCUSSION, NEXT STEPS
1:00 PM	CONCLUSION OF WORKSHOP

WEDNESDAY, 19 APRIL (Drafting Committee Meeting)

1:30 PM – 5:00 PM	Drafting of conclusions and recommendations from workshop

APPENDIX 4

International Arctic Development Policy Declarations Since 1987



A timeline depicting the proliferation of actions directed at considering Arctic development pathways since the 1980s. International policy documents are positioned below the timeline, with their U.S. counterparts positioned above. Numbers denote declarations, documents and actions that are defined below. Colors indicate documents that are similar in jurisdiction, scope or concept. These collectively illustrate the acceleration of declarations over the past decade, reflecting the growing strategic importance of the Arctic. After Berkman (2015).

1. Gorbachev—"Pole of Peace" Speech (October 1987)
2. Arctic Environmental Protection Strategy (June 1991)
3. COSPAR Convention (September 1992)
4. Arctic Council-Ottawa Declaration (September 1996)
5. Arctic Military Environmental Cooperation Declaration (September 1996)
6. Arctic Council-Iqaluit Declaration (September 1998)
7. Arctic Council Barrow Declaration (October 2000)
8. Arctic Council-Inari Declaration (October 2002)
9. IMO Guidelines for Arctic Ice-Covered Waters (December 2002)
10. Arctic Council Reykjavik Declaration (November 2004)
11. Arctic Council-Salekhard Declaration (October 2006)
12. Norway's High North Strategy (December 2006)
13. Illulissat Declaration (May 2008)
14. Russian State Policy on the Arctic (September 2008)
15. European Parliament Resolution (October 2008)
16. European Commission Communication (November 2008)
17. United States Arctic Region Policy (January 2009)
18. Canada's Northern Strategy (March 2009)
19. Circumpolar Inuit Declaration on Arctic Sovereignty (April 2009)
20. Arctic Council-Tromso Declaration (April 2009)
21. European Council Conclusions (December 2009)
22. IMO Guidelines for Polar Waters (December 2009)
23. Finland's Strategy for the Arctic (July 2010)
24. European Parliament Resolution (January 2011)
25. Sweden's Arctic Strategy (May 2011)
26. Arctic Council Nuuk Declaration (May 2011)
27. Arctic Search and Rescue Agreement (May 2011)
28. Iceland's Arctic Policy (August 2011)
29. Denmark's Arctic Strategy (August 2011)
30. European Parliament-Council Communication (June 2012)
31. United States National Strategy for the Arctic (May 2013)
32. Arctic Council-Kiruna Declaration (May 2013)
33. Arctic Marine Oil Pollution Agreement (May 2013)
34. Finland's New Strategy for the Arctic (August 2013)
35. UK Policy Towards the Arctic (October 2013)

REFERENCES

Aagaard, K., and E. C. Carmack (1989). The role of sea ice and other fresh water in the arctic circulation. *Journal of Geophysical Research-Oceans*, 94:14485–14498, https://doi.org/10.1029/JC094iC10p14485.

ACIA (2004). *Impacts of a Warming Arctic: Arctic Climate Impact Assessment (ACIA) Overview Report*. Cambridge University Press, 140 pp.

ACIA (2005). *Arctic Climate Impact Assessment*. New York: Cambridge University Press, 1042 pp.

Adams, J. D., G. C. Black, J. R. Clemmons, and P. E. Stephan (2005). Scientific teams and institutional collaborations: Evidence from U.S. Universities, 1981–1999. *Research Policy*, 34:259–285, https://doi.org/10.1016/j.respol.2005.01.014.

Alley, R. (2007). Wally was right: Predictive ability of the North Atlantic "Conveyor Belt" Hypothesis for abrupt climate change. *Annual Review of Earth and Planetary Sciences*, 35:241–272, https://doi.org/10.1146/annurev.earth.35.081006.131524.

Alvarez, R. A., S. W. Pacala, J. J. Winebrake, W. L. Chameides, and S. P. Hamburg (2012). Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences of the United States of America,* 109(17):6435–6440, https://doi.org/10.1073/pnas.1202407109.

AMAP (2012). Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost. SWIPA 2011 Overview Report. Oslo: Arctic Monitoring and Assessment Programme (AMAP), xi + 97 pp.

Andrew, R. (2014). Socio-Economic Drivers of Change in the Arctic (SEDoCA). Oslo, Norway: CICERO Center for International Climate and Environmental Research.

AON (2018). United States Arctic Observing Network, NOAA Arctic Program, https://www.arctic.noaa.gov/Arctic-News/ArtMID/5556/ArticleID/386/United-States-Arctic-Observing-Network.

AON Design and Implementation Task Force (2012). Designing, Optimizing and Implementing an Arctic Observing Network (AON): A Report by the AON Design and Implementation (ADI) Task Force. Fairbanks, AK: Study and Environmental Arctic Change (SEARCH), 64 pp.

Archer, D. (2007). Methane hydrate stability and anthropogenic climate change. *Biogeosci Discuss*, 4(2), pp. 993–1010.

Arctic CHAMP (2014). Freshwater Integration study (FWI) Synthesis Page. Arctic CHAMP (Community-wide Hydrologic Analysis and Monitoring Program) website, available at http://arcticchamp.sr.unh.edu/synthesis/index.shtml.

Arctic Council (2017). *Declaration of the Foreign Ministers of the Arctic States at the 10th Ministerial meeting of he Arctic Council, held in Fairbanks, Alaska, 10-11 May 2017*. https://oaarchive.arctic-council.org/handle/11374/1910.

Arctic Energy Center (2016). How Do Arctic Reserves Stack Up? http://arcticenergycenter.com/how-do-arctic-reserves-stack-up/.

ARCUS (2007a). The Arctic Synthesis Collaboratory: An Integrated Community-based Research Network. Arctic Collaboratory Planning Committee and ARCSS Committee, eTown Meeting, 5 Dec 2007, http://archive.arcus.org/arcss/etm/december_07/ArcticCollaboratory_ETown_Dec07FINAL.ppt.

ARCUS (2007b). Personal communication to Simon Stephenson, Arctic Sciences Division, Office of Polar Programs, National Science Foundation: Arctic System Synthesis Workshop: New Perspectives through Data Discovery and Modeling, workshop summary, Seattle, Washington, 2-4 April 2007, 16 pp.

ARCUS (2010). Arctic System Science Program, available at https://archive.arcus.org/arcss/message.html.

ARCUS (2014a). Arctic Synthesis Collaboratory. Arctic Research Consortium of the United States, available at http://www.arcus.org/search/content/Arctic%20Synthesis%20Collaboratory.

ARCUS (2014b). Reports and Science Plans, Study of Environmental Arctic Change. Available at http://www.arcus.org/search-program/resources/reports-and-science-plans.

ARCUS (2018a). Conducting Research with Northern Communities: Documented practices and resources for productive, respectful relationships between researchers and community members, https://www.arcus.org/resources/northern-communities.

ARCUS (2018b). Sea Ice for Walrus Outlook (SIWO). https://www.arcus.org/search-program/siwo.

Arrigo, K.R., and G.L. van Dijken (2015). Continued increases in Arctic Ocean primary production. *Progress in Oceanography* 136:60–70, https://doi.org/10.1016/j.pocean.2015.05.002.

Arrigo, K. R., G. van Dijken, and S. Pabi (2008). Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters*, *35*(19), https://doi.org/10.1029/2008GL035028.

Baron, J. S., A. Specht, E. Garnier, P. Bishop, C. A. Campbell, F. W. Davis, B. Fady, D. Field, L. J. Gross, S. Guru, C. R. McClain, J. N. Parker, R. Price, C. H. Rawson, A. Rodrigo, L. A. Sheble, and M. Winter (2017). Synthesis Centers as Critical Research Infrastructure. *BioScience*, 67(8):750–759, https://doi.org/10.1093/biosci/bix053.

Bazilchuk, N. (2013). An arctic animal community crashes in response to extreme weather events. *ScienceNordic*, http://sciencenordic.com/arctic-animal-community-crashes-response-extreme-weather-events.

Bennett, L. M., and H. Gadlin (2012). Collaboration and team science: From theory to practice. *Journal of Investigative Medicine*, 60(5):768–775, https://doi.org/10.2310/JIM.0b013e318250871d.

Berkman, P. A. (2015). Institutional dimensions of Sustaining Arctic Observing Networks (SAON). *Arctic*, 68(1), https://doi.org/10.14430/arctic4499.

Berkman, P. A. (2017). Evidence for informed decision-making to achieve Arctic sustainability. North Pacific Arctic Conference, East-West Center, Honolulu, Hawaii, August 2017.

Berkman, P. A., L. Kullerud, A. Pope, A. N. Vylegzhanin, and O. R. Young (2017a). Science Diplomacy, The Arctic Science Agreement propels science diplomacy. *Science*, 358(6363):596–598, https://doi.org/10.1126/science.aaq0890.

Berkman, P. A., M. A. Lang, D. W. H. Walton, and O. R. Young (2017b). Science *Diplomacy: Science, Antarctica, and the Governance of International Spaces*. Smithsonian Institute Scholarly Press, Washington, 351 pp.

Bos, N., A. Zimmerman, J. Olson, J. Yew, J. Yerkie, E. Dahl, and G. Olson (2007). From shared databases to communities of practice: A taxonomy of collaboratories. *Journal of Computer-Mediated Communication*, 12:652–672, https://doi.org/10.1111/j.1083-6101.2007.00343.x.

Bosolovich, M. G., F. R. Robertson, L. Takaks, A. Molod, and D. Mocko (2017). Atmospheric water balance and variability in the MERRA-2 reanalysis. *Journal of Climate*, 30:1177–1196, https://doi.org/10.1175/JCLI-D-16-0338.1.

Boucher, O., P. Friedlingstein, B. Collins, and K. P. Shine (2009). The indirect global warming potential and global temperature change potential due to methane oxidation. *Environmental Research Letters*, 4(4):044007, https://doi.org/10.1088/1748-9326/4/4/044007.

Bradbury, J. A., S. L. Dingman, and B. D. Keim (2002). New England drought and relations with large scale atmospheric circulation patterns. *J Am Water Resour Assoc* 38(5):1,287–1,299, https://doi.org/10.1111/j.1752-1688.2002.tb04348.x.

Broecker, W. S., J. P. Kennett, B. P. Flower, J. T. Teller, S. Trumbore, G. Bonani, and W. Wolfli (1989). Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. *Nature*, 341(6240):318, https://doi.org/10.1038/341318a0.

Bush, G. R. (2013). The appreciative inquiry model. In, E. H. Kessler [Ed.], *Encyclopedia of Management Theory*, Sage Publications, 1:41–44.

Bush, President G. W. (2009). *U.S. Arctic Policy*. National Security Presidential Directive/NSPD-66, Homeland Security Presidential Directive/HSPD-25.

Callaghan, T.V., M. Johansson, R. D. Brown P. Ya. Groisman, N. Labba, V. Radionov, R. S. Bradley, S. Blangy, O. N. Bulygina, T. R. Christensen, and others (2011). Multiple effects of changes in Arctic snow cover. *Ambio* 40:32–45, https://doi.org/10.1007/s13280-011-0213-x.

Carpenter, S. R., E. V. Armbrust, P. W. Arzberger, F. S. Chapin III, J. J. Elser, et al. (2009). Accelerate synthesis in ecology and environmental sciences. *BioScience*, 59:699–701, https://doi.org/10.1525/bio.2009.59.8.11.

Carson, M. and G. Peterson (eds.) 2016. *Arctic Resilience Report*. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm. http://www.arctic-council.org/arr.

Cassano, J. J., A. DuVivier, A. Roberts, M. Hughes, M. Seefeldt, M. Brunke, A. Craig, B. Fisel, W. Gutowski, J. Hamman, M. Higgins, W. Maslowski, B. Nijssen, R. Osinski, and X. Zeng (2017). Development of the Regional Arctic System Model (RASM): Near surface atmospheric climate, sensitivity. *Journal of Climate*, 30:5729–5753, https://doi.org/10.1175/JCLI-D-15-0775.1.

Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, 556:191–196, https://doi.org/10.1038/s41586-018-0006-5.

Chan, S. C., E. J. Kendon, H. J. Fowler, S. Blenkinsop, C.A. T. Ferro, and D. B. Stephenson (2012). Does increasing the spatial resolution of a regional climate model improve the simulated daily precipitation? *Climate Dynamics*, 41:1475–1495, https://doi.org/10.1007/s00382-012-1568-9.

Chen, C. H., and P. G. Ho (2008). Statistical pattern recognition in remote sensing. *Pattern Recognition* 41(9):2731–2741, https://doi.org/10.1016/j.patcog.2008.04.013.

Cherkauer, K. A., L. C. Bowling, and D. P. Lettenmaier (2003). Variable infiltration capacity cold land process model updates. *Global and Planetary Change*, 38(1-2):151–159, https://doi.org/10.1016/S0921-8181(03)00025-0.

Clement, J. P., J. L. Bengtson, and B. P. Kelly (2013). *Managing for the Future in a Rapidly Changing Arctic: A Report to the President*. Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska (D.J. Hayes, Chair), Washington, DC, 59 pp.

Clement Kinney, J. and W. Maslowski (2012). On the oceanic communication between the Western Subarctic Gyre and the deep Bering Sea. *Deep-Sea Research Part I*, 66:11–25, https://doi.org/10.1016/j.dsr.2012.04.001.

Clilverd, H. M., D. M. White, A. C. Tidwell, and M. A. Rawlins (2011). The sensitivity of northern groundwater recharge to climate change: A case study in northwest Alaska. *Journal of the American Water Resources Association*, 47(6):1228–1240, https://doi.org/10.1111/j.1752-1688.2011.00569.x.

Climate Reanalyzer (2018). Climate Change Institute, University of Maine, USA, (http://cci-reanalyzer.org/).

Cohen, J., M. Barlow, P. Kushner, and K. Saito (2007). Stratosphere-troposphere coupling and links with Eurasian land-surface variability. *Journal of Climate*, 20:5335–5343, https://doi.org/10.1175/2007JCLI1725.1.

Cohen, J., J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, 7:627–637, https://doi.org/10.1038/ngeo2234.

Cohen, M. (2015). Paradigm Shift: How expert opinions keep changing on life, the universe and everything. Imprint Academic, Exeter, UK, 200 pp.

Connolly, C. T., M. S. Khosh, G. Burkart, T. A. Douglas, R. M. Holmes, A. D. Jacobson, S. E. Tank, and J. W. McClelland (2018). Watershed slope as a predictor of fluvial dissolved organic matter and nitrate concentrations across geographical space and catchment size in the Arctic. *Geophysical Research Letters,* (*in review*).

Cook, N. J. and M. L. Hilton [Eds.] (2015). Enhancing the Effectiveness of Team Science. *National Academies Press*, Washington, 268 pp, https://www.nap.edu/read/19007/chapter/4.

CUAHSI (2004). *A National Center for Hydrologic Synthesis: Scientific Objectives, Structure, and Implementation*. Washington, DC: Consortium of Universities for the Advancement of Hydrologic Science, Inc., 22 pp.

Dai, A. (2006). Precipitation characteristics in eighteen coupled climate models. *Journal of Climate*, 19(18):4605–4630, https://doi.org/10.1175/JCLI3884.1.

Darrah, T. H., A. Vengosh, R. B. Jackson, N. R. Warner, and R. J. Poreda (2014). Noble gases identify mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. *Proceedings of the National Academy of Sciences of the United States of America*, 111(39):14,076–14,081, https://doi.org/10.1073/pnas.1322107111.

Dee, D. P., S. M. Uppala, A. J. Simmons, et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137:553–597, https://doi.org/10.1002/qj.828.

Deep Cold (2018). Deep Cold: Interior and Northern Alaska Weather & Climate, An Alaskan Weather and Climate Blog. http://ak-wx.blogspot.com/, Accessed 13 July 2018.

Diallo, M., B. Tonn, P. Alvarez, P. Bardet, K. Chong, D. Feldman, R. Mahajan, N. Scott, R. G. Urban, and E. Yablonovitch (2013). Implications: Convergence of Knowledge and Technology for a Sustainable Society. Chapter 9, in: Roco, M. C., W. S. Bainbridge, B. Tonn, and G. Whitesides (eds.). *Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies,* New York, Springer.

DOE (2018). https://climatemodeling.science.energy.gov/projects/energy-exascale-earth-system-model, accessed 24 May 2018.

Drake, T. W., K. P. Wickland, R. G. M. Spencer, D. M. McKnight and R. G. Striegl (2015). Ancient low–molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw. *PNAS,* 112: 13946-13951.

Dyurgerov, M. B. and C. L. Carter (2004). Observational evidence of increases in freshwater inflow to the Arctic Ocean. *Arctic, Antarctic, and Alpine Research*, 36(1):117–122.

Entekhabi, D., E. Njoku, P. O'Neill, K. Kellogg, W. Crow, W. Edelstein, J. Entin, S. Goodman, T. Jackson, J. Johnson, J. Kimball, J. Piepmeier, R. Koster, K. McDonald, M. Moghaddam, S. Moran, R. Reichle, J. C. Shi, M. Spencer, S. Thurman, L. Tsang, and J. van Zyl (2010). The Soil Moisture Active and Passive (SMAP) Mission. *Proceedings of the IEEE*, 98(5):704–716, https://doi.org/10.1109/JPROC.2010.2043918.

Epstein, H., U. Bhatt, M. Raynolds, D. Walker, B. C. Forbes, M. Macias-Fauria, M. Loranty, G. Phoenix and J. Bjerke (2016). Tundra Greenness. In: *Arctic Report Card 2016*, http://www.arctic.noaa.gov/Report-Card.

ESMF (2017). Earth System Modeling Framework, available online at www.earthsystemcog.org/projects/esmf/.

Fasullo, J.T., and K.E. Trenberth (2008). The annual cycle of the energy budget. Part II: Meridional structures and poleward transports. *Journal of Climate*, 21(10): 2313–2325, https://doi.org/10.1175/2007JCLI1936.1.

Forbes, B. C., T. Kumpula, N. Meschtyb, R. Laptander, M. Macias-Fauria, P. Zetterberg, M. Verdonen, A. Skarin, K.-Y. Kim, L. N. Boisvert, J. C. Stroeve, and A. Bartsh (2016). Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia, *Biology Letters*, 12:20160466, https://doi.org/10.1098/rsbl.2016.0466.

Francis, J. (2014). Rapid Arctic warming and extreme weather events in mid-latitudes: Are they connected? Keynote presentation at the National Science Foundation International Workshop on Communicating the Science and Impacts of Fundamental Earth System Change: A Focus on Ice-Snow-Water. Washington, DC, November 12–14, 2014.

Francis, J. A. (2018). Meltdown. *Scientific American*, 318:48–53, https://doi.org/10.1038/scientificamerican0418-48.

Francis, J. A., W. Chan, D. Leathers, J. R. Miller, and D. E. Veron (2009b). Winter Northern Hemisphere weather patterns remember summer Arctic sea ice extent. *Geophysical Research Letters*, 36:L07503, https://doi.org/10.1029/2009GL037274.

Francis, J. A. and S. J. Vavrus (2015). Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters* 10, http://dx.doi.org/10.1088/1748-9326/10/1/014005.

Francis, J. A., D. M. White, J. J. Cassano, W. J. Gutowski Jr., L. D. Hinzman, M. M. Holland, M. A. Steele, and C. J. Vörösmarty (2009a). An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life. *Journal of Geophysical Research*, 114:G04019, https://doi.org/10.1029/2008JG000902.

Frey, K. E., and J. W. McClelland (2009). Impacts of permafrost degradation on Arctic river biogeochemistry. *Hydrological Processes*, 23(1):169–182, https://doi.org/10.1002/hyp.7196.

Frey, K. E., and L. C. Smith (2005). Amplified carbon release from vast West Siberian peatlands by 2100. *Geophysical Research Letters*, 32(9), https://doi.org/10.1029/2004GL022025.

Fritz, K., J. E. Vonk, and H. Lantuit (2017). Collapsing Arctic coastlines. *Nature Climate Change*, 7:6–7, https://doi.org/10.1038/nclimate3188.

Furtado, J. C., J. L. Cohen, A. H. Butler, E. E. Riddle, and A. Kumar (2015). Eurasian snow cover variability, winter climate, and stratosphere-troposphere coupling in the CMIP5 models. *Climate Dynamics*, 45:2591–2605, https://doi.org/10.1007/s00382-015-2494-4.

Ganji A., L. Sushama, D. Verseghy, and R. Harvey (2017). On improving cold region hydrological processes in the Canadian Land Surface Scheme. *Theoretical and Applied Climatology*, 127(1-2):45–59. https://doi.org/10.1007/s00704-015-1618-4.

Gelaro, R., W. McCarty, M. J. Suarez, et al. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERERA-2). *Journal of Climate,* 30:5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1.

Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, P. H. Worley, Z.-L. Yang, and M. Zhang (2011). The Community Climate System Model Version 4. *Journal of Climate*, 24:4973–4991.

Green, C. H. and A. J. Pershing (2007). Climate drives sea change. *Science*, 315(5815):1084–1085, https://doi.org/10.1126/science.1136495.

Greenwald, M. J., W. B. Bowden, M. N. Gooseff, J. P. Zarnetske, J. P. McNamara, J. H. Bradford, and T. R. Brosten (2008). Hyporheic exchange and water chemistry of two arctic tundra streams of contrasting geomorphology. *Journal of Geophysical Research-Biogeosciences*, 113(G2), https://doi.org/10.1029/2007JG000549.

Griffin, C. G., J. W. McClelland, K. E. Frey, G. Fiske, and R. M. Holmes (2018). Quantifying CDOM and DOC in major Arctic rivers during ice-free conditions using Landsat TM and ETM+ data. *Remote Sensing of Environment*, 209:395–409, https://doi.org/10.1016/j.rse.2018.02.060.

Groisman, P. Y., B. Sun, R. S. Vose, J. H. Lawrimore, P. H. Whitfield, E. Førland, I. Hanssen-Bauer, M. C. Serreze, V. N. Razuvaev, and G. V. Alekseev (2003). Contemporary climate changes in high latitudes of the Northern Hemisphere: Daily time resolution. In *14th Symposium on Global Change and Climate Variations*, pp. 9–13.

Guglielmo, F., I. Stemmler, and G. Lammel (2012). The impact of organochlorines cycling in the cryosphere on their global distribution and fate–1. Sea ice. *Environmental Pollution*, 162:475-481, https://doi.org/10.1016/j.envpol.2011.09.039.

Hamilton, L. C. and M. Lemcke-Stampone (2014). Arctic warming and your weather: Public belief in the connection. *International Journal of Climatology*, 334:1723–1728, https://doi.org/10.1002/joc.3796.

Hampton, S. E., and J. N. Parker (2011). Collaboration and productivity in scientific synthesis. *BioScience*, 61:900–910, https://doi.org/10.1525/bio.2011.61.11.9.

Hansen-Bauer, I., and E.J. Førland (1998). Long-term trends in precipitation and temperature in the Norwegian Arctic: Can they be explained by changes in atmospheric circulation patterns? *Climate Research* 10(2):143–153, https://doi.org/10.3354/cr010143.

Hayes, D. J., A. D. McGuire, D. W. Kicklighter, K. R. Gurney, T. J. Burnside, and J. M. Melillo (2011). Is the northern high latitude land-based CO_2 sink weakening? *Global Biogeochemical Cycles*, 25:GB3018, https://doi.org/10.1029/2010GB003813.

Heavens, N. G., D. S. Ward, and N. M. Mahowald (2013). Studying and projecting climate change with Earth system models. *Nature Education Knowledge*, 4(5):4.

Hinzman, L. D., C. J. Deal, A. D. McGuire, S. H. Mernild, I. V. Polyakov, and J. E. Walsh (2013). Trajectory of the Arctic as an integrated system. *Ecological Applications*, 23:1837–1868, https://doi.org/10.1890/11-1498.1.

Holland, M. M., J. Finnis, A. P. Barrett, and M. C. Serreze (2007 Projected changes in Arctic Ocean freshwater budgets. *Journal of Geophysical Research-Biogeosciences*, 112, G04S55, https://doi.org/10.1029/2006JG000354.

Holland, M. M., D. A. Bailey, and S. Vavrus (2010). Inherent sea ice predictability in the rapidly changing Arctic environment of the Community Climate System Model, version 3. *Climate Dynamics*, 36(1):239–253, https://doi.org/10.1007/s00382-010-0792-4.

Holland-Bartels, L., and B. Pierce (Eds.) (2011). An evaluation of the science needs to inform decisions on Outer Continental Shelf energy development in the Chukchi and Beaufort Seas, Alaska. *U.S. Geological Survey Circular 1370*, 278 pp.

Houghton, R. A. (2007). Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences*, 35:313–347, https://doi.org/10.1146/annurev.earth.35.031306.140057.

Hugelius, G., J. Strauss, S. Zubrzycki, J. W. Harden, E. Schuur, C. L. Ping, … and J. A. O'Donnell (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, 11(23):6573–6593, https://doi.org/10.5194/bg-11-6573-2014.

IARPC (2016). *Arctic Research Plan FY2017-2021*. Interagency Arctic Research Policy Committee of the National Science and Technology Council. 84 pp.

IGBP (2018). IGBP Book Series, International Geosphere-Biosphere Programme, http://www.igbp.net/publications/igbpbook-series.4.d8b4c3c12bf3be638a8000924.html. Accessed 4 May 2018.

IIASA AFI (2018). Arctic Futures Initiative, International Institute for Applied Systems Analysis, http://www.iiasa.ac.at/web/home/research/afi/arctic-futures.html.

Inuit Circumpolar Council-Alaska (2015). *Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective*. Technical Report. Inuit Circumpolar Council-Alaska, Anchorage, AK, 116 pp.

IPCC (1996). *Climate Change 1995: The Science of Climate Change* (J. T. Houghton, L. G. Miera Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell, Eds.), Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 572 pp.

IPCC (2007a). Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. [M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [R. K. Pachauri and A. Reisinger (Eds.)]. Geneva, Switzerland: IPCC, 104 pp.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (Eds.)]. Cambridge and New York: Cambridge University Press, 1535 pp.

Jahn, A., L. B. Tremblay, R. Newton, M. M. Holland, L. A. Mysak, and I. A. Dmitrenko (2010). A tracer study of the Arctic Ocean's liquid freshwater export variability. *Journal of Geophysical Research-Oceans*, 115(C7), https://doi.org/10.1029/2009JC005873.

Jeffries, M., J. Overland, and D. Perovich (2013). The Arctic shifts to a new normal. *Physics Today*, 66(10) 35–40, https://doi.org/10.1063/PT.3.2147.

Joly, K., and D. R. Klein (2016). Complexity of Caribou Population Dynamics in a Changing Climate. *U.S. National Park Service*, https://www.nps.gov/articles/aps-v10-i1-c7.htm.

Jones, B. M., C. A. Baughman, V. E. Romanovsky, A. D. Parsekian, E. L. Babcock, E. Stephani, M. C. Jones, G. Grosse, and E. E. Berg (2016). Presence of rapidly degrading permafrost plateaus in south-central Alaska. *The Cryosphere*, 10:2673–2692, https://doi.org/10.5194/tc-10-2673-2016.

Jones, M. C., J. Harden, J. O'Donnell, K. Manies, T. Jorgenson, C. Treat, and S. Ewing (2017). Rapid carbon loss and slow recovery following permafrost thaw in boreal peatlands. *Global Change Biology*, 23(3):1109–1127, https://doi.org/10.1111/gcb.13403.

Joughin, I., S. B. Das, M. A. King, B. E. Smith, I. M. Howat, and T. Moon (2008). Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science*, 320(5877):781–783, https://doi.org/10.1126/science.1153288.

Kaplan, J. O., N. H. Bigelow, I. C. Prentice, S. P. Harrison, P. J. Bartlein, T. R. Christensen, W. Cramer, N. V. Matveyeva, A. D. McGuire, D. F. Murray, V. Y. Razzhivin, B. Smith, D. A. Walker, P. M. Anderson, A. A. Andreev, L. B. Brubaker, M. E. Edwards, and A. V. Lozhkin (2003). Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections. *Journal of Geophysical Research-Atmospheres*, 108(D19), https://doi.org/10.1029/2002JD002559.

Kashiwase, H., K. I. Ohshima, S. Nihashi, and J. Eicken (2017). Evidence for ice-ocean albedo feedback in the Arctic Ocean shifting to a seasonal ice zone. *Nature Scientific Reports*, 7:8170, https://doi.org/10.1038/s41598-017-08467-z.

Kattsov, V. M., J. E. Walsh, W. L. Chapman, V. A. Govorkova, T. V. Pavlova, and X. Zhang (2007). Simulation and projection of Arctic freshwater budget components by the IPCC AR4 global climate models. *Journal of Hydrometeorology*, 8(3):571–589, https://doi.org/10.1175/JHM575.1.

Kaufman, D. S., T. A. Ager, N. J. Anderson, et al. (2004). Holocene thermal maximum in the western Arctic (0–180 W). *Quaternary Sci Rev*, 23: 529–560.

Kintisch, E. (2014). NewsFocus: Into the Maelstrom. *Science*, 344: 250–253, https://doi.org/10.1126/science.344.6181.250.

Koenig, L., S. Martin, M. Studinger, and J. Sonntag (2010). Polar Airborne Observations Fill Gap in Satellite Date. *EOS Transactions, American Geophysical Union*, 91(38), https://doi.org/10.1029/2010eo380002.

Kopp, R.E., A. C. Kemp, K. Bittermann, B. P. Horton, J. P. Donnelly, W. R. Gehrels, C. C. Hay, J. X. Mitrovica, E. D. Morrow, and S. Rahmstorf (2016). Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences of the United States of America*, 113:E1434–E1441, https://doi.org/10.1073/pnas.1517056113.

Koven, C. D., B. Ringeval, P. Friedlingstein, P. Ciais, P. Cadule, D. Khvorostyanov, G. Krinner, and C. Tarnocai (2011). Permafrost carbon-climate feedbacks accelerate global warming. *Proceedings of the National Academy of Sciences of the United States of America*, 108(36):14,769–14,774, https://doi.org/10.1073/pnas.1103910108.

Krawchuk, M.A. and S.G. Cumming (2011). Effects of biotic feedback and harvest management on boreal forest fire activity under climate change. *Ecological Applications*, 21(1):122–136, https://doi.org/10.1890/09-2004.1.

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B*, 363:815–830, https://doi.org/10.1098/rstb.2007.2185.

Laprise, R., R. de Elía, D. Caya, S. Biner, P. Lucas-Picher, E. Diaconescu, M. Leduc, A. Alexandru, and L. Separovic (2008). Challenging some tenets of Regional Climate Modelling. *Meteorology and Atmospheric Physics*, 100:3–22, https://doi.org/10.1007/s00703-008-0292-9.

Lashof, D. A., and D. R. Ahuja (1990). Relative contributions of greenhouse gas emissions to global warming. *Nature*, 344(6266):529, https://doi.org/10.1038/344529a0.

Lawrence, D. M., C. D. Koven, S. C. Swenson, W. J. Riley, and A. G. Slater (2015). Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO_2 and CH_4 emissions. *Environmental Research Letters*, 10(9):094011, https://doi.org/10.1088/1748-9326/10/9/094011.

Lawrence, D. M. and A. G. Slater (2010). The contribution of snow condition trends to future ground climate. *Climate Dynamics*, 34(7-8):969–981, https://doi.org/10.1007/s00382-009-0537-4.

Lawrence, D. M., A. G. Slater, V. E. Romanovsky, and D. J. Nicolsky (2008). Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *Journal of Geophysical Research-Earth*, 113(F2), https://doi.org/10.1029/2007JF000883.

Lawrence, D. M., A. G. Slater, and S. C. Swenson (2012). Simulation of present-day and future permafrost and seasonally frozen ground conditions in CCSM4. *Journal of Climate*, *CCSM4 Special Collection*, 25:2207–2225, https://doi.org/10.1175/JCLI-D-11-00334.1.

Lee, S. (2014). A Theory for polar amplification from a general circulation perspective. *Asia-Pacific Journal of Atmospheric Sciences*, 50:31–42, https://doi.org/10.1007/s13143-014-0024-7.

Lee, Y. J., P. A. Matrai, M. A. Friedrichs, V. S. Saba, O. Aumont, et al. (2016). Net primary productivity estimates and environmental variables in the Arctic Ocean: An assessment of coupled physical-biogeochemical models. *Journal of Geophysical Research-Oceans*, 121(12):8635–8669, https://doi.org/10.1002/2016JC011993.

Levin, D. (2017). Ice roads ease isolation in Canada's North, but they're melting too soon. *The New York Times,* https://www.nytimes.com/2017/04/19/world/canada/ice-roads-ease-isolation-in-canadas-north-but-theyre-melting-too-soon.html.

Lewis, E. L., E. P. Jones, P. Lemke, T. D. Prowse, and P. Wadhams (2000). *The Freshwater Budget of the Arctic Ocean.* NATO Science Series 2. *Environmental Security*, Vol. 70. Dordrecht: Kluwer Academic Publishing. 623 pp.

Liljedahl, A., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y. Lijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J. Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona (2016). Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, 9(4):312–318, https://doi.org/10.1038/ngeo2674.

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang (2014). Evaluation of seven different atmospheric reanalysis products in the Arctic. *Journal of Climate*, 27:2588–2606, https://doi.org/10.1175/JCLI-D-13-00014.1.

Mackay, D., and F. Wania (1995). Transport of contaminants to the Arctic: partitioning, processes and models. *Science of the Total Environment*, 160–161:25–38, https://doi.org/10.1016/0048-9697(95)04342-X.

Mann, P. J., R. G. Spencer, P. J. Hernes, J. Six, G. R. Aiken, S. E. Tank, J. W. McClelland, K. D. Butler, R. Y. Dyda, and R. M. Holmes (2017). Pan-arctic trends in terrestrial dissolved organic matter from optical measurements. *Frontiers in Earth Science*, 4:25, https://doi.org/10.3389/feart.2016.00025.

McClelland, J. W., R. M. Holmes, B. J. Peterson, and M. Stieglitz (2004). Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *J Geophys Res-Oceans*, 109: D18102, https://doi.org/10.1029/2004JD004583.

McDonald, K. C., J. S. Kimball, E. Njoku, R. Zimmermann, and M. Zhao (2004). Variability in springtime thaw in the terrestrial high latitudes: Monitoring a major control on the biospheric assimilation of atmospheric CO2 with spaceborne microwave remote sensing. *Earth Interact*, 8(20): 1-23.

McGuire, A. D., D. J. Hayes, D. W. Kicklighter, M. Manizza, Q. Zhuang, M. Chen, M. J. Follows, K. R. Gurney, J. W. McClelland, J. M. Melillo, and B. J. Peterson (2010). An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus B*, 62(5):455–474, https://doi.org/10.1111/j.1600-0889.2010.00497.x.

McGuire, A. D., J. M. Melillo, D. W. Kicklighter, Y. Pan, X. Xiao, J. Helfrich, B. Moore, C. J. Vörösmarty, and A. L. Schloss (1997). Equilibrium responses of global net primary production and carbon storage to doubled atmospheric carbon dioxide: Sensitivity to changes in vegetation nitrogen concentration. *Global Biogeochemical Cycles*, 11(2):173–189, https://doi.org/10.1029/97GB00059.

McNamara J. P., D. L. Kane, and L. D. Hinzman (1999). An analysis of an arctic channel network using a digital elevation model. *Geomorphology*, 29(3-4):339–353, https://doi.org/10.1016/S0169-555X(99)00017-3.

Meier, W. N., G. K. Hovelsrud, B. E. H. van Oort, J. R. Key, K. M. Kovacs, C. Michel, C. Haas, M. A. Granskog, S. Gerland, D. K. Petrovich, A. Makshtas, and J. D. Reist (2014). Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity. *Reviews of Geophysics*, 52(3):185–217, https://doi.org/10.1002/2013RG000431.

Melillo, J. M., T. C. Richmond, and G. W. Yohe (Eds.) (2014). Climate Change Impacts in the United States: The Third National Climate Assessment. Washington, DC: U.S. Global Change Research Program, 841 pp., https://doi.org/10.7930/J0Z31WJ2.

MIT (2011). *The Third Revolution: The Convergence of the Life Sciences, Physical Sciences, and Engineering*. Washington Office.

Moore, J. A., M. C. Serreze, D. Middleton, M. Ramamurthy, and L. Yarmey (2013). *The Arctic Cooperative Data and Information System: Data Management Support for the NSF Arctic Research Program*. Proceedings of the International Forum on Polar Data Activities in Global Data Systems, 19 pp., Tokyo, Japan, 15-16 October 2013.

Morlighem, M., E. Rignot, and J. K. Willis (2016). Improving bed topography mapping of Greenland glaciers using NASA's Oceans Melting Greenland (OMG) data. *Oceanography* 29(4):62–71, https://doi.org/10.5670/oceanog.2016.99.

Mortin, J., T. M. Schroder, A. W. Hansen, B. Holt, and K. C. McDonald (2012). Mapping of seasonal freeze-thaw transitions across the pan-Arctic land and sea ice domains with satellite radar. *Journal of Geophysical Research-Oceans*, 117, C08004, https://doi.org/10.1029/2012JC008001.

Murray, M. S., L. Anderson, G. Cherkashov, C. Cuyler, B. Forbes, J. C. Gascard, C. Haas, P. Schlosser, G. Shaver, K. Shimada, M. Tjernström, J. Walsh, J. Wandell, and Z. Zhao (2010). The International Study of Arctic Change: Science Plan. Stockholm: ISAC International Program Office, 58 pp.

Myers-Smith, I. H., B. C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K. D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Lévesque, and S. Boudreau (2011). Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. *Environmental Research Letters*, 6(4):045509, https://doi.org/10.1088/1748-9326/6/4/045509.

NAS (2014). Transportation Research Board and National Research Council. *Responding to Oil Spills in the U.S. Arctic Marine Environment*. Washington, DC: The National Academies Press, https://doi.org/10.17226/18625.

NASA (2012). IceBridge Arctic 2012 Field Campaign, https://www.nasa.gov/mission_pages/icebridge/multimedia/spr12/ARC_2012_flights_all.html, accessed 12 July 2018.

NASA (2018). Oceans Melting Greenland (OMG), https://omg.jpl.nasa.gov/portal/, accessed 12 July 2018.

NASA (2018). MODIS: Moderate Resolution Imaging Spectroradiometer, NASA TERRA: The EOS Flagship, https://terra.nasa.gov/about/terra-instruments/modis.

NCP (2013). *Canadian Arctic Contaminants Assessment Report On Persistent Organic Pollutants – 2013*. [D. Muir, P. Kurt-Karakus, and J. Stow (Eds)]. Northern Contaminants Program, Aboriginal Affairs and Northern Development Canada, Ottawa, ON.

Newton, R., S. Pfirman, B. Tremblay, and P. DeRepentigny (2017). Increasing transnational sea-ice exchange in a changing Arctic Ocean. *Earth's Future*, 5(6):633–647, https://doi.org/10.1002/2016EF000500.

Nghiem, S. V., D. K. Hall, T. L. Mote, M. Tedesco, M. R. Albert, K. Keegan, C. A. Schuman, N. E. DiGirolamo, and G. Neumann (2012). The extreme melt across the Greenland ice sheet in 2012, *Geophysical Research Letters*, 39:L20502, https://doi.org/10.1029/2012GL053611.

Nghiem, S. V., D. K. Hall, I. G. Rigor, P. Li, and G. Neumann (2014). Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. *Geophysical Research Letters*, 41(3):873–879, https://doi.org/10.1002/2013GL058956.

Nicolsky, D. J., V. E. Romanovsky, V. A. Alexeev, and D. M. Lawrence (2007). Improved modeling of permafrost dynamics in a GCM land-surface scheme. *Geophysical Research Letters*, 34(8):L08501, https://doi.org/10.1029/2007GL029525.

Niu, G. Y. and Z. L. Yang (2006). Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. *Journal of Hydrometeorology*, 7(5):937–952, https://doi.org/10.1175/JHM538.1.

NOAA ESRL (2018). 20th Century Reanalysis, https://www.esrl.noaa.gov/psd/data/20thC_Rean/.

NRC (2010). *Research at the Intersection of the Physical and Life Sciences*. Washington, DC: The National Academies Press.

NRC (2013). *Abrupt Impacts of Climate Change: Anticipating Surprises*. Polar Research Board, Committee on Understanding and Monitoring Abrupt Climate Change and its Impacts, Board on Atmospheric Sciences and Climate, co-authored by J. W. C. White, R. B. Alley, D. Archer, A. D. Barnosky, J. Foley, R. Fu, M. Holland, S. Lozier, J. Schmitt, L. C. Smith, G. Sugihara, D. Thompson, and A. Weaver. National Research Council, Washington, DC: The National Academies Press, 208 pp.

NRC (2014). *The Arctic in the Anthropocene: Emerging Research Questions*. Polar Research Board, Committee on Emerging Research Questions in the Arctic, co-authored by H. Huntington, S. Pfirman, C. Ashjian, L. Bourgeau-Chavez, J. A. Francis, S. Haakanson, R. Hawley, T. Hepa, D. Hik, L.D. Hinzman, A. Lynch, A. M. Macrander, G. Miller, K. Moran, E. Mosley-Thompson, S. Mukasa, and T. Weingartner. National Research Council, Washington, DC: The National Academies Press, 220 pp.

NRC-COHS (2011). Global Change and Extreme Hydrology: Testing Conventional Wisdom. National Research Council Committee on Hydrologic Science, National Research Council, Washington, DC.

NSF (National Science Foundation)/DOC (Department of Commerce) (2002). *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science.* Edited by M.C. Roco and W.S. Bainbridge, National Science Foundation. Publ. by: Kluwer Acad. Publ., currently Springer, Dordrecht, 2003. (Available on: www.wtec.org/ConvergingTechnologies//1/NBIC_report.pdf).

NSF (2018). https://www.nsf.gov/news/special_reports/big_ideas/index.jsp, accessed 24 May 2018.

NSIDC (2018). Arctic Sea Ice News and Analysis. National Snow and Ice Data Center, https://nsidc.org/arcticseaicenews/.

Obama, President B. (2014). *Implementation Plan for The National Strategy for the Arctic Region*, 33 pp.

Obama, President B. (2015). Executive Order – Enhancing Coordination of National Efforts in the Arctic. http://www.whitehouse.gov/the-press-office/2015/01/21/executive-order-enhancing-coordination-national-efforts-arctic.

Obbard, R. W., S. Sadri, Y. Q. Wong, A. A. Khitun, I. Baker, and R. C. Thompson (2014). Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future*, 2(6):315–320, https://doi.org/10.1002/2014EF000240.

Oelkers, E. H. and D. R. Cole (2008). Carbon dioxide sequestration: A solution to the global problem. *Elements*, 4:305–310, https://doi.org/10.2113/gselements.4.5.305.

Ogi, M. and J. M. Wallace (2007). Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation, *Geophysical Research Letters*, 34, L12705, https://doi.org/10.1029/2007GL029897.

Olason, E. and D. Notz (2014). Drivers of variability in Arctic sea ice drift speed, *Journal of Geophysical Research-Oceans*, 119:5755-5775, https://doi.org/10.1002/2014JC009897.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, D. P. van Vuuren (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climate Change*, 122:387–400, https://doi.org/10.1007/s10584-013-0905-2.

Overeem, I., R. S. Anderson, C. W. Wobus, *et al.* (2011). Sea ice loss enhances wave action at the Arctic coast. *Geophysical Research Letters*, 38, L17503, https://doi.org/10.1029/2011GL048681.

Overland, J. E. (2016). Is the melting Arctic changing midlatitude weather? *Physics Today*, 69:38, https://doi.org/10.1063/PT.3.3107.

Overpeck, J. T., M. Sturm, J. A. Francis, D. K. J. Perovich, M. C. Serreze, R. Benner, E. C. Carmack, F. S. Chapin III, S. C. Gerlach, L. C. Hamilton, M. Holland, H. P. Huntington, J. R. Key, A. H. Lloyd, G. M. MacDonald, J. A. McFadden D. Noone, T. D. Prowse, P. Schlosser, and C. Vörösmarty (2005). Arctic system on trajectory to new, seasonally ice-free state. *Eos Transactions*, *American Geophysical Union*, 86(34):309, https://doi.org/10.1029/2005EO340001.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A. I. Shiklomanov, and S. Rahmstorf (2002). Increasing river discharge to the Arctic Ocean. *Science*, 298(5601):2171–2173, https://doi.org/10.1126/science.1077445.

Petoukhov, V., M. Claussen, A. Berger, M. Crucifix, M. Eby, A. V. Eliseev, T. Fichefet, A. Ganopolski, H. Goosse, I. Kamenkovich, I. I. Mokhov, M. Montoya, L. A. Mysak, A. Sokolov, P. Stone, Z. Wang, and A. J. Weaver (2005). EMIC Intercomparison Project (EMIP-CO$_2$): Comparative analysis of EMIC simulations of climate and equilibrium and transient responses to atmospheric CO$_2$ doubling. *Climate Dynamics*, 25:363–385, https://doi.org/10.1007/s00382-005-0042-3.

Petty, A. A., J. C. Stroeve, P. R. Holland, L. N. Boisvert, A. C. Bliss, N. Kimura, and W. N. Meier (2018), The Arctic sea ice cover of 2016: A year of record-low highs and higher-than-expected lows. *The Cryosphere*, 12:433–452, https://doi.org/10.5194/tc-12-433-2018.

Pfirman, S. L., H. Eicken, D. Bauch, and W. F. Weeks (1995). Potential transport of pollutants by Arctic sea ice. *Science of the Total Environment*, 159:129–146, https://doi.org/10.1016/0048-9697(95)04174-Y.

Pfirman, S., C. Fowler, B. Tremblay, and R. Newton (2009). The Last Arctic sea ice refuge. *The Circle*, 4:6–8.

Plumb, A. (1989). On the seasonal cycle of stratospheric planetary waves. *Pure and Applied Geophysics,* 130:233–242, https://doi.org/10.1007/BF00874457.

Polyakov, I. V., A. V. Pnyushkov, M. B. Alkire, I. M. Ashik, T. M. Baumann, E. C. Carmack, I. Goszczko, J. Guthrie, V. V. Ivanov, T. Kanzow, R. Krishfield, R. Kwok, A. Sundfjord, J. Morison, R. Rember, and A. Yulin (2017). Greater role for Atlantic inflows on sea ice loss in the Eurasian Basin of the Arctic Ocean. *Science*, 356, https://doi.org/10.1126/science.aai8204.

Praetorius S. K. (2018). North Atlantic circulation slows down. *Nature*, 556:180–181, https://doi.org/10.1038/d41586-018-04086-4.

Rahmstorf, S., J. E. Box, G. Feulner, M. E. Mann, A. Robinson, S. Rutherford, and E. J. Schaffernicht (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, 5:475–480, https://doi.org/10.1038/nclimate2554.

Ramanathan, V., B. R. Barkstrom, and E. F. Harrison (1992). Climate and the Earth's radiation budget. *AIP Conference Proceedings*, 247(1):55–77, https://doi.org/10.1063/1.41922.

Rawlins, M. A., R. B. Lammers, S. Frolking, B. M. Fekete, and C. J. Vörösmarty (2003). Simulating pan-Arctic runoff with a macro-scale terrestrial water balance model. *Hydrological Processes*, 17(13):2521–2539, https://doi.org/10.1002/hyp.1271.

Rawlins, M. A., D. J. Nicolsky, K. C. McDonald, and V. E. Romanovsky (2013). Simulating soil freeze/thaw dynamics with an improved pan-Arctic water balance model. *Journal of Advances in Modeling Earth Systems*, 5(4):659–675, https://doi.org/10.1002/jame.20045.

Rawlins, M. A., M. C. Serreze, R. Schroeder, X. Zhang, and K. C. McDonald (2009b). Diagnosis of the record discharge of Arctic-draining Eurasian river in 2007. *Environmental Research Letters*, 4, https://doi.org/10.1088/1748-9326/4/4/045011.

Rawlins, M. A., M. Steele, M. M. Holland, J. C. Adam, J. E. Cherry, J. A. Francis, P. Y. Groisman, L. D. Hinzman, T. G. Huntington, D. L. Kane, J. S. Kimball, and Coauthors (2010). Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations. *Journal of Climate*, 23(21):5715–5737, https://doi.org/10.1175/2010JCLI3421.1.

Rawlins, M. A., M. Steele, M. C. Serreze, C. J. Vörösmarty, W. Ermold, R. B. Lammers, K. C. McDonald, T. M. Pavelsky, A. Shiklomanov and J. Zhang (2009a). Tracing freshwater anomalies through the air-land-ocean system: A case study from the Mackenzie River basin and the Beaufort Gyre. *Atmos-Ocean*, 47(1):79–97, https://doi.org/10.3137/OC301.2009.

Rawlins, M. A., C. J. Willmott, A. Shiklomanov, S. Frolking, and C. J. Vörösmarty (2006). Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean. *Geophysical Research Letters*, 33:L07403, https://doi.org/10.1029/2005GL025231.

Raymond-Yakoubian, B. and J. Raymond-Yakoubian (2017). Research processes and indigenous communities in western Alaska: Results from a workshop on indigenous perspectives. *Witness the Arctic*, Fall 2017, Issue 2.

Ritchey, T. (1991, Reprint 1996). Analysis and synthesis: On scientific method – Based on a study by Bernhard Riemann. *Systems Research* 8(4):21–41, https://doi.org/10.1002/sres.3850080402.

Roberts, A., J. Cherry, R. Döscher, S. Elliott, and L. Sushama (2011). Exploring the potential for Arctic system modeling. *Bulletin of the American Meteorological Society*, 92:203–206, https://doi.org/10.1175/2010BAMS2959.1.

Roberts, A., L. D. Hinzman, J. E. Walsh, M. Holland, J. Cassano, R. Döscher, H. Mitsudera, and A. Sumi (2010). *A Science Plan for Regional Arctic System Modeling: A report by the Arctic Research Community for the National Science Foundation Office of Polar Programs*. International Arctic Research Center Technical Paper 10-0001. International Arctic Research Center, University of Alaska Fairbanks, 47 pp.

Roco, M. C., W. S. Bainbridge, B. Tonn, and G. Whitesides (eds.) (2013). *Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies*. Final Report, May 2013. New York, Springer.

Romanovsky, V. E., D. S. Drozdov, N. G. Oberman, G. V. Malkova, A. L. Kholodov, S. S. Marchenko, N. G. Moskalenko, D. O. Sergeev, N. G. Ukraintseva, A. A. Abramov, D. A. Gilichinsky, and A. A. Vasiliev (2010a). Thermal state of permafrost in Russia. *Permafrost and Periglacial Processes* 21:136–155, https://doi.org/10.1002/ppp.683.

Romanovsky, V., S. Smith, and H. Christiansen (2010b). Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007–2009: A synthesis. *Permafrost and Periglacial Processes*, 21:106–116, https://doi.org/10.1002/ppp.689.

Rosenzweig B., C. Vörösmarty, W. Gutowski, and A.L. Steiner (2014). Joining scientists and stakeholders in regional Earth system modeling. *Eos, Transactions American Geophysical Union*, 95(27):247–248, https://doi.org/10.1002/2014EO270005.

Ruppel, C. D. (2011). Methane hydrates and contemporary climate change. *Nature Education Knowledge*, 3(10):29.

Russell, D. and A. Gunn (2012). Caribou and Reindeer (Rangifer). In: Arctic Report Card: *Update for 2012.* http://www.arctic.noaa.gov/report12/caribou_reindeer.html.

Saha, S., S. Moorthi, H-Lu Pan, et al. (2010). The NCEP Climate Forecast System Reanalysis. *Bulletin of the American Meteorological Society*, 91(8)1015–1057, https://doi.org/10.1175/2010BAMS3001.1.

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y.-T. Hou, H. Chuang, M. Iredell, M. Ek, J. Meng, R. Yang, M. Peña Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker (2014). The NCEP Climate Forecast System Version 2. *Journal of Climate*, 27:2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1.

Saito, K., T. Zhang, D. Yang, S. Marchenko, R. G. Barry, V. Romanovsky, and L. D. Hinzman (2013). Influence of the physical terrestrial Arctic in the eco-climate system. *Ecological Applications*, 23:1778-1797, https://doi.org/10.1890/11-1062.1.

SAON (2008). Observing the Arctic: Report of the Sustaining Arctic Observing Networks (SAON) Initiating Group, 16 pp.

SAON (2018). Sustaining Arctic Observing Networks, https://www.arcticobserving.org/.

Sand, M., T. K. Berntsen, O. Seland, and J. E. Kristjánsson (2013). Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes. *Journal of Geophysical Research-Atmospheres*, 118:7788–7798, https://doi.org/10.1002/jgrd.50613.

Schellnhuber, H. J. (2009). Tipping elements in the Earth System. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49):20,561–20,563, https://doi.org/10.1073/pnas.0911106106.

Schroeder, R., M. A. Rawlins, K. C. McDonald, E. Podest, R. Zimmermann, and M. Kueppers (2010). Satellite microwave remote sensing of North Eurasian inundation dynamics: Development of coarse-resolution products and comparison with high-resolution synthetic aperture radar data. *Environmental Research Letters*, 5(1): 015003, https://doi.org/10.1088/1748-9326/5/1/015003.

Schuur, E. A. G., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, and S. A. Zimov (2008). Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience*, 58:701–714, https://doi.org/10.1641/B580807.

Schuur, E. A. G., A.D. McGuire, C. Schädel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E. Romanovsky, K. Schaefer, M. R. Turetsky, C. C. Treat, and J. E. Vonk (2015). Climate change and the permafrost carbon feedback. *Nature*, 520(7546):171–179, https://doi.org/10.1038/nature14338.

Seitzinger, S. P., O. Gaffney, G. Brasseur, W. Broadgate, P. Ciais, M. Claussen, J. W. Erisman, T. Kiefer, C. Lancelot, P. S. Monks, K. Smyth, J. Syvitski, and M. Uematsu (2016). International Geosphere–Biosphere Programme and Earth system science: Three decades of co-evolution. *Anthropocene*, 12:3–16, https://doi.org/10.1016/j.ancene.2016.01.001.

Sepp, M. and J. Jaagus (2011), Changes in the activity and track of Arctic cyclones. *Climate Change*, 105:577–595, https://doi.org/10.1007/s10584-010-9893-7.

Serreze, M. C., A. P. Barrett, A. J. Slater, M. Steele, J. Zhang, and K. E. Trenberth (2007). The large-scale energy budget of the Arctic. *Journal of Geophysical Research*, 112:D11122, https://doi.org/10.1029/2006JD008230.

Serreze, M. C., A. P. Barrett, A. G. Slater, R. A. Woodgate, K. Aagaard, R. B. Lammers, M. Steele, R. Moritz, M. Meredith, and C. M. Lee (2006). The large-scale freshwater cycle of the Arctic. *Journal of Geophysical Research*, 111:C11010, https://doi.org/10.1029/2005JC003424.

Serreze, M. C., A. Crawford, and A. P. Barrett (2015). Extreme daily precipitation events at Spitsbergen, an Arctic island. *Int J Climatol*, doi:10.1002/joc.4308.

Serreze, M. C., J. Stroeve, A. P. Barrett, and L. N. Boisvert (2016). Summer atmospheric circulation anomalies over the Arctic Ocean and their influences on September sea ice extent: A cautionary tale. *Journal of Geophysical Research-Atmospheres*, 121(19), https://doi.org/10.1002/2016JD025161.

Shakhova, N., I. Semiletov, O. Gustafsson, V. Sergienko, L. Lobkovsky, O. Dudarev, V. Tumskoy, M. Grigoriev, A. Mazurov, A. Salyuk, and R. Ananiev (2017). Current rates and mechanisms of subsea permafrost degradation in the East Siberian Arctic Shelf. *Nature Communications*, 8:15872, https://doi.org/10.1038/ncomms15872.

Shakhova, N., I. Semiletov, I. Leifer, A. Salyuk, P. Rekant, and D. Kosmach (2010). Geochemical and geophysical evidence of methane release over the East Siberian Arctic Shelf. *Journal of Geophysical Research-Oceans*, 115(C8), https://doi.org/10.1029/2009JC005602.

Shakhova, N., I. Semiletov, and G. Panteleev (2005). The distribution of methane on the Siberian Arctic shelves: Implications for the marine methane cycle. *Geophysical Research Letters*, 32(9), https://doi.org/10.1029/2005GL022751.

Shiklomanov, I. (1993). World fresh water resources, Chapter 2 in *Water in Crisis: A Guide to the Worlds Fresh Water Resources*, [Ed. P. H. Gleick], p. 13–24.

Shkolnik, I., T. Pavlova, S. Efimov, and S. Zhuravlev (2018). Future changes in peak river flows across northern Eurasia as inferred from an ensemble of regional climate projections under the IPCC RCP8.5 scenario. *Climate Dynamics*, 50(1–2):215–230, https://doi.org/10.1007/s00382-017-3600-6.

Sitch, S., C. Huntingford, N. Gedney, P. E. Levy, M. Lomas, S. L. Piao, R. Betts, P. Ciais, P. Cox, P. Friedlingstein, and C. D. Jones (2008). Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, 14(9):2015–2039, https://doi.org/10.1111/j.1365-2486.2008.01626.x.

Smith, S., V. Romanovsky, A. Lewkowicz, C. Burn, M. Allard, G. Clow, K. Yoshikawa, and J. Throop (2010). Thermal state of permafrost in North America: A contribution to the International Polar Year. *Permafrost and Periglacial Processes*, 21:117–135, https://doi.org/10.1002/ppp.690.

Smolarkiewicz, P. W. Deconinck, M. Hamrud, C. Kühnlein, G. Mozdzynski, J. Szmelter, and N. Wedi. 2015. An all-scale, finite volume module for the IFS. *ECMWF Newsletter* 145:24–29.

Sonne, C., R.J. Letcher, B.M. Jenssen, J.-P. Desforges, I. Eulaers, E. Andersen-Ranberg, K. Gustavson, B. Styrishave, and R. Dietz (2017). A veterinary perspective on One Health in the Arctic. *Acta Veterinaria Scandinavica*, 59:84, https://doi.org/10.1186/s13028-017-0353-5.

Spreen, G., L. Kaleschke, and G. Heygster (2008). Sea ice remote sensing using AMSR-E 89 GHz channels *Journal of Geophysical Research*, 113, C02S03, https://doi.org/10.1029/2005JC003384.

Srokosz, M., M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke, and R. Sutton (2012). Past, present and future change in the Atlantic meridional overturning circulation. *Bulletin of the American Meteorological Society*, 93(11):1663-1676, https://doi.org/10.1175/BAMS-D-11-00151.1.

Studinger, M., L. Koenig, S. Martin, and J. Sonntag (2010). Operation Icebridge: Using instrumented aircraft to bridge the observational gap between Icesat and Icesat-2. 2010 IEEE International Geoscience and Remote Sensing Symposium, 1918-1919, https://doi.org/10.1109/Igarss.2010.5650555.

Su, F., J. C. Adam, L. C. Bowling, and D. P. Lettenmaier (2005). Streamflow simulations of the terrestrial Arctic domain. *Journal of Geophysical Research-Atmospheres*, 110(D8), https://doi.org/10.1029/2004JD005518.

Su, F., J. C. Adam, K. E. Trenberth, and D. P. Lettenmaier (2006). Evaluation of surface water fluxes of the pan-Arctic land region with a land surface model and ERA-40 reanalysis. *Journal of Geophysical Research-Atmospheres*, 111(D5), https://doi.org/10.1029/2005JD006387.

Swanberg, N. and R. M. Holmes (2013). Is it ARCSS? *Witness the Arctic*, 17:4–6.

Swenson, S. C., D. M. Lawrence, and H. Lee (2012). Improved simulation of the terrestrial hydrological cycle in permafrost regions by the Community Land Model. *Journal of Advances in Modeling Earth Systems*, 4(3), https://doi.org/10.1029/2012MS000165.

Tans, P. and R. Keeling (2018). NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

Tape, K. E. N., M. Sturm, and C. Racine (2006). The evidence for shrub expansion in northern Alaska and the Pan-Arctic. G*lobal Change Biology*, 12(4):686–702, https://doi.org/10.1111/j.1365-2486.2006.01128.x.

Thornalley, D. J. R., D. W. Oppo, P. Ortega, J. I. Robson, C. M. Brierly, R. Davis, I. R. Hall, P. Moffa-Sanchez, N. L. Rose, P. T. Spooner, I. Yashayaev, and L. D. Keigwin (2018). Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, 556:227–230, https://doi.org/10.1038/s41586-018-0007-4.

Tietche, S., D. Notz, J. H. Jungclaus, and J. Marotzke (2011). Recovery mechanisms of Arctic summer sea ice. *Geophys Res Lett*, 38, L02707, https://doi.org/10.1029/2010GL045698.

Treat, C. C., W. M. Wollheim, R. K. Varner, A. S. Grandy, J. Talbot, and S. Frolking (2014). Temperature and peat type control CO_2 and CH_4 production in Alaskan permafrost peats. *Global Change Biology*, 20:2674–2686, https://doi.org/10.1111/gcb.12572.

Troy, T. J., J. Sheffield, and E. F. Wood (2012). The role of winter precipitation and temperature on northern Eurasian streamflow trends. *Journal of Geophysical Research-Atmospheres*, 117(D5), https://doi.org/10.1029/2011JD016208.

UCAR (2018). Multimedia Gallery – IPCC Assessment Reports. https://www2.ucar.edu/news/understanding-climate-change-multimedia-gallery

USARC (2010). *Scaling Studies in Arctic System Science and Policy Support: A Call-to-Research.* C.J. Vörösmarty, D. McGuire, and J. Hobbie (eds.). A report from the U.S. Arctic Research Commission. U.S. Arctic Research Commission, Arlington, VA. 84 pp.

USARC (2012). *Oil Spills in Arctic Waters: An Introduction and Inventory of Research Activities and USARC Recommendations*. U.S. Arctic Research Commission and the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory.

USARC (2016). Goals and Objectives for Arctic Research: 2015–2016. U.S. Arctic Research Commission, Arlington VA, 28 pp., https://storage.googleapis.com/arcticgov-static/publications/goals/usarc_goals_2015-2016.pdf.

U.S. Department of State (2017). *Fairbanks Declaration 2017: On the Occasion of the Tenth Ministerial Meeting of the Arctic Council*. https://www.state.gov/e/oes/rls/other/2017/270802.htm.

van Vuuren, D. P., E. Kriegler, B. C. O'Neill, K. L. Ebi, K. Riahi, R. R. Carter, J. Edmonds, S. Hallegatte, T. Kram, R. Mathur, and H. Winkler (2014). A new scenario framework for Climate Change Research: scenario matrix architecture. *Climate Change*, 122:373–386, https://doi.org/10.1007/s10584-013-0906-1.

Vonk, J. E., S. E. Tank, W. B. Bowden, I. Laurion, W. G. Vincent, P. Alekseychik, M. Amyot, M. F. Billet, J. Canario, R. M. Cory, and B. N. Deshpande (2015). Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. *Biogeosciences*, 12(23):7129–7167, https://doi.org/10.5194/bg-12-7129-2015.

Vörösmarty, C. J., P. A. Davídsson, M. A. K. Muir and R. W. Sandford (2015). *Motivating Research on the Science Communications Front: Conveying the Nature and Impacts of Rapid Change in Ice-Dominated Earth Systems to Decision Makers and the Public*. A report to the National Science Foundation, 48 pp.

Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. Lammers (2000). Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles*, 14:599–621, https://doi.org/10.1029/1999GB900092.

Vörösmarty, C. J. and L. D. Hinzman (2016). Arctic change – So what?: Linkages and impacts. In: *Arctic Report Card 2016*, http://www.arctic.noaa.gov/Report-Card.

Vörösmarty, C. J., L. D. Hinzman, B. J. Peterson, D. L. Bromwich, L. Hamilton, J. Morison, V. Romanovsky, M. Sturm, and R. Webb (2001). *The Hydrologic Cycle and its role in Arctic and global environmental change: A rationale and strategy for synthesis study*. Fairbanks, AK: ARCUS, 84 pp.

Vörösmarty, C. J., L. D. Hinzman, and J. Pundsack (2008). Introduction to the special section on Changes in the Arctic Freshwater System: Identification, attribution, and impacts at local and global scales. *Journal of Geophysical Research-Biogeosciences*, 113:G01S91, https://doi.org/10.1029/2007JG000615.

Walter Anthony, K. M., M. E. Edwards, G. Grosse, S. A. Zimov, and F. S. Chapin III (2007). Thermokarst lakes as a source of atmospheric CH4 during the last deglaciation. *Science*, 318:633–636, https://doi.org/10.1126/science.1142924.

Walter Anthony, K. M., S. A. Zimov, G. Grosse, M. C. Jones, P. M. Anthony, F. S. Chapin III, J. C. Finlay, M. C. Mack, S. Davydov, P. Frenzel, and S. Frolking (2014). A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature*, 511(7510):452–456, https://doi.org/10.1038/nature13560.

Wang, R. (2017). *Climate Change and Ice Road Operations*. Ausenco, http://www.ausenco.com/ice-road-op-climate-change.

Waugh, D. W., A. H. Sobel, and L. M. Polvani (2017). What is the polar vortex and how does it influence weather? *Bulletin of the American Meteorological Society*, 98(1): 37-44, https://doi.org/10.1175/BAMS-D-15-00212.1.

White, D. M., L. Hinzman, L. Alessa, J. Cassano, et al. (2007). The Arctic freshwater system: Changes and impacts. *Journal of Geophysical Research*, 112, G04S54, https://doi.org/10.1029/2006JG000353.

Williscroft, K., S. E. Grasby, B. Beauchamp, C. T. Little, K. Dewing, D. Birgel, T. Poulton, and K. Hryniewicz (2017). Extensive Early Cretaceous (Albian) methane seepage on Ellef Ringnes Island, Canadian High Arctic. *Geological Society of America Bulletin*, 129(7–8):788–805, https://doi.org/10.1130/B31601.1.

Woo, M. K., D. L. Kane, S. K. Carey, and D. Yang (2008). Progress in permafrost hydrology in the new millennium. *Permafrost and Periglacial Processes*, 19(2):237–254, https://doi.org/10.1002/ppp.613.

Woodgate, R. A., T. J. Weingartner, and R. Lindsay (2012). Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column. *Geophysical Research Letters*, 39, L24603, https://doi.org/10.1029/2012GL054092.

Woodhouse M., G. Mann, K. Carslaw, and O. Boucher (2013). Sensitivity of cloud condensation nuclei to regional changes in dimethyl-sulphide emissions. *Atmospheric Chemistry and Physics*, 13:2723–2733, https://doi.org/10.5194/acp-13-2723-2013.

World Economic Forum (2015). *Arctic Investment Protocol: Guidelines for Responsible Investment in the Arctic*. http://www3.weforum.org/docs/WEF_Arctic_Investment_Protocol.pdf.

Wu, P., R. Wood, and P. Stott (2005). Human influence on increasing Arctic river discharges. *Geophysical Research Letters*, 32(2), https://doi.org/10.1029/2004GL021570.

Yi, Y., J. S. Kimball, M. A. Rawlins, M. Moghaddam, and E. S. Euskirchen (2015). The role of snow cover affecting boreal-arctic soil freeze–thaw and carbon dynamics. *Biogeosciences*, 12(19): 5811–5829, https://doi.org/10.5194/bg-12-5811-2015.

Zarnetske J. P., M. N. Gooseff, T. R. Brosten, J. H. Bradford, J. P. McNamara, and W. B. Bowden (2007). Transient storage as a function of geomorphology, discharge, and permafrost active layer conditions in Arctic tundra streams. *Water Resources Research*, 43(7):W07410, https://doi.org/10.1029/2005WR004816.

Zhang, J., R. Lindsay, A. Schweiger, and M. Steele (2013). The impact of an intense summer cyclone on 2012 Arctic sea ice retreat. *Geophysical Research Letters*, 40:720–726, https://doi.org/10.1002/grl.50190.

Zhang, J., W. Tian, M. P. Chipperfield, F. Xie, and J. Huang (2016). Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades. *Nat Clim Ch*, 6(12), https://doi.org/10.1038/nclimate3136.

Zhang, K., B. C. Douglas, and S. P. Leatherman (2004). Global warming and coastal erosion. *Climate Change*, 64:41–58, https://doi.org/10.1023/B:CLIM.0000024690.32682.48.

Zhang, X., J. He, J. Zhang, I. Polyakov, R. Gerdes, J. Inoue, and P. Wu (2012). Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nature Climate Change,* https://doi.org/10.1038/nclimate1631.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen (2002). Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, 297(5579):218–222, https://doi.org/10.1126/science.1072708.

JULY 2018