SCALING STUDIES IN ARCTIC SYSTEM SCIENCE AND POLICY SUPPORT

A CALL-TO-RESEARCH

A REPORT FROM THE
U.S. ARCTIC RESEARCH COMMISSION

COVER PHOTOS

TOP LEFT TO BOTTOM RIGHT | Belugas in the Bering Sea seen during the April 2006 U.S. Fish and Wildlife Service (USFWS) Walrus Survey (photo by USFWS/Brad Benter). | *Polar Sea* and *Louis S. St. Laurent* at end of Arctic Ocean Crossing, north of Svalbard (photo by Knut Aagaard). | Sampling across ice field on the Arctic ocean (photo by Knut Aagaard). | Sunset (photo by Leopoldo Llinas). | Sitting on top of submarine after breaking through the ice (photo by Bernard Coakley).
BACKGROUND | Iceberg in the Svalbard Islands, Norway (iStockphoto).

ABOUT THE U.S. ARCTIC RESEARCH COMMISSION

The U.S. Arctic Research Commission is a small, independent federal agency established in 1984 by the Arctic Research and Policy Act (Public Law 98-373, July 31, 1984; amended as Public Law 101-609, November 16, 1990). The Commission's principal duties are: (1) to establish the national policy, priorities, and goals necessary to construct a federal program plan for basic and applied scientific research with respect to the Arctic, including natural resources and materials, physical, biological and health sciences, and social and behavioral sciences; (2) to promote Arctic research, to recommend Arctic research policy, and to communicate research and policy recommendations to the President and the Congress; (3) to work with the National Science Foundation as the lead agency responsible for implementing the Arctic research policy and to support cooperation and collaboration throughout the Federal Government; (4) to give guidance to the Interagency Arctic Research Policy Committee to develop national Arctic research projects and a five-year plan to implement those projects; and (5) to interact with Arctic residents, international Arctic research programs and organizations, and local institutions, including regional governments to obtain the broadest possible view of Arctic research needs.

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EDITED BY CHARLES J. VÖRÖSMARTY,
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LETTER FROM THE CHAIR

Dear Colleague,

As a non-scientist student of the Arctic, I have had the opportunity to meet and hear from the best polar scientists in the world, working in many disciplines. We share common views: the Arctic is changing, the change is important to the world, and how fast it changes—and exactly how—will have great impacts. As citizen taxpayers, many of these changes will require us to make large investments. Some changes, such as accelerated permafrost thawing or more frequent forest fires, will constrain the way we live and operate in the Arctic. Others, such as new sea routes or new fisheries, will bring economic opportunity to the North and greater value to the world.

These realizations are fueled by a highly dynamic and expanding body of scientists—scientists who are contributing fundamental knowledge about how the Arctic works and how it is changing. Part of this community's success results from the incredibly broad scope of their studies, measurements, and models that have been developed over the past two decades.

Scientists study the North from various perspectives using various platforms. Satellites give us a better-than-birds-eye view of receding ice conditions in the aggregate, for example, but a scientist with a drill is still required to confirm the thickness of the ice at any given point. Observation of the fluxes of gases to or from plots of ground, a few square meters in area, may tell us how Arctic tundra is "breathing" at a detailed level, but the value of these collected data to climate scientists—and policymakers—may have meaning only when the information is extrapolated over vast expanses.

For example, some have recently suggested that the amount of methane out-gassing from the tundra is sufficiently large, on a pan-Arctic scale, that it needs to be accounted for when compiling global carbon inventories and fluxes. To meet the needs of Arctic Ocean fisheries regulators and shippers, we will need to improve our sea-ice models so that they can more accurately predict ice cover over the entire basin. The models must be able to forecast conditions in any given port, at any given time, where fishing or shipping may be based. We can estimate changing weather patterns on a grand scale, but we can't say whether more or less precipitation will impact the habitat or productivity of a local fishery.

Macro and micro? Lump your observations or split them? Small scale or large? When it comes to understanding processes in the Arctic, what does the very small tell us about the very large? What does the aggregate dynamics tell us about the smaller pieces that make up the full system? What

does the region tell us about the locality? How many buoys are needed? How many sensors from the bottom of the sea to the upper atmosphere are necessary, to be sure we know what we think we know about changing climate in the North? These and many other questions constitute the essence of the scaling problem.

While these issues are hardly restricted to Arctic science, they become particularly relevant in the North. Within a global climate context, this region is recognized as constituting a strongly coupled and highly sensitive system. To understand the role of the Arctic in global change—both as generator and recipient of impacts—requires knowledge of the behavior of many interacting components that traditionally have been sampled, simulated, and studied at relatively fine scales. To me, "scaling" issues must be better understood if science will be able to deliver on its goal of better understanding and predicting the state of the Arctic with a high degree of accuracy and precision.

Two USARC Commissioners, Dr. John Hobbie and Dr. Charles J. Vörösmarty, both scientists, brought these many issues to our attention. The aims of this report are to: (i) increase awareness of the great diversity of approaches to Arctic research, with respect to scales of time and space, (ii) identify impediments to progress should scale-related issues not be addressed, and (iii) identify opportunities that will improve the status quo and spark new innovations across otherwise isolated parts of the research spectrum. We also discuss how scaling issues should be considered in the public policy domain. If not, we will fail a generation of human beings who are relying on our work—in climate, biodiversity, the humanities and other sciences, but also in energy, engineering, and a broad swath of decisions that have social and economic relevance.

A typical audience for a U.S. Arctic Research Commission report is the membership of Interagency Arctic Research Policy Committee (IARPC). These agencies carry out research goals set by the Commission, but it is the science community itself that, in adhering to the scientific method, sets standards of measurement and analysis—as ultimately judged by peer review—that give us confidence that the "facts" we're finding are truly facts. In this report, we call on the science community, as well as its sponsors, to pay closer attention to the many aspects of scaling that present themselves today—as both challenges and opportunities—that should become part of the larger Arctic research agenda.

Mead Treadwell, Chair
U.S. Arctic Research Commission
Anchorage, Alaska, June 3, 2010

EXECUTIVE SUMMARY

A goal of the U.S. Arctic Research Commission is to assist U.S. agencies in establishing a national Arctic research program. In 2003, the Commission recognized the changes already happening in the Arctic environment because of climate warming and the need to synthesize available information, regardless of the scale at which they were collected, to predict impacts on the whole Arctic. The first workshops to discuss this required data synthesis were held in Seattle in 2003 and Woods Hole in 2004, and they brought together six experts in scaling up to the regional level through models of hydrology and of plant response to climate change. The next workshop, held in Seattle in 2008, included more than 20 experts in Arctic environmental processes and scaling in the fields of atmospheric modeling, ocean physics, biology, river hydrology, terrestrial ecology, and the interactions of human populations with climate change. This report, organized at the Seattle meeting, is not intended to be a comprehensive synthesis of existing data and models but instead is a call for action to fill the gaps in the knowledge necessary to reach the goal of developing an understanding of the effects of climate and environmental changes at the scale of the whole Arctic environment including their atmospheric, marine, terrestrial, and human components.

SYNTHESIS FINDING 1. Scaling issues and even the definitions of scale are so varied across individual disciplines that they hinder interdisciplinary research. There exists a great breadth of spatial and temporal scales that characterize any one Arctic disciplinary science and its applications, which is matched by an equally broad admixture of spatial and temporal scales when comparing disciplines. Such diversity arises due to the differences in the historical development of individual disciplines and the resulting unique nomenclatures regarding scale—for example, the microscale means something radically different to a microbial ecologist than to an Arctic Ocean sea ice modeler. Discipline-specific approaches to scaling have made it difficult for different disciplines to effectively integrate. One way forward is to cast grand challenge research questions built around transdisciplinarity as well as multiscale perspectives to understand the current and future states of the fully coupled Arctic system involving all key natural and human components.

SYNTHESIS FINDING 2. Scale incongruities among components of the Arctic system give rise to opportunities to study intermediate scales. The existing body of research has focused traditionally on measurements made at local scales, which are important for understanding the inherent dynamics of discipline-specific processes. These same disciplines have also relied on coarse-scale models to achieve understanding over the broad domain. In contrast, intermediate spatial and temporal scales have received relatively less attention, yet it is precisely along the interface of intermediate scales that systems are often critically defined, for example, through boundary layer fluxes linking the highly heterogeneous Arctic land surface to a well-mixed overlying atmosphere. Intermediate scales, or mesoscales, provide an important context through which coarse-scale dynamics become useful in setting the bounds of key phenomena and fine-scale dynamics can be generalized. Difficult numerical stability challenges face the modeling community across scales. These challenges must be solved to ensure stable numerical "handshakes" across contrasting time/length scales. These stable handshakes set the stage for robust Arctic systems models that can then be useful for informing policy decisions.

SYNTHESIS FINDING 3. Thresholds are scale-sensitive and important, yet prove difficult to detect, study, and/or predict. Threshold responses occur at the point where there is an abrupt change in a system quality, property, or

phenomenon, or where small changes in a driving variable of the system produces large, persistent, and potentially irreversible responses. Thresholds represent tipping points, and involve time and space "edge effects." A key to identifying thresholds is proper representation of interactions of processes across a spectrum of scales. Again, within this spectrum, the intermediate scale may be critical; more work needs to be focused within this space-time domain.

SYNTHESIS FINDING 4. Scales of human perception are much different than those associated with the study of natural systems. Arctic human systems are complex and multifaceted, encompassing both indigenous and industrial societies that vary greatly in their domains of perception and human footprints. Traditional societies have evolved the capacity to detect and understand the implications of changes in Arctic systems and have adapted using strategies through which they can cope with local shortages in renewable resources. For example, they may utilize a higher level of mobility to make use of a much larger spatial domain for hunting and gathering. Viewed as a scaling issue, native populations have developed strategies to effectively reduce the impact of high-frequency "noise" in the landscape by integrating their interactions over a wider domain, which tends to dampen such variations. Decision-making in industrial societies also spans many spatial scales. Modern-day institutional and legal frameworks can be found at individual village, provincial, national, and international levels. In an age of globalization, macro-level decisions on the Arctic can easily fail to establish links to processes operating in the Arctic itself and of relevance to people and livelihoods. Studying the perceptions of space-time domains and Arctic system change by traditional as well as modern Arctic communities will help to better understand our society's readiness to adapt to Arctic environmental change.

SYNTHESIS FINDING 5. Information has not been well structured to facilitate cross-scale studies. Given the reality of a diverse treatment of space-time issues within and across disciplines, it is not surprising that coherent information systems are not yet in place to reconcile or deal with these incongruities. Social and natural scientists organize information over very different accounting units (e.g., administrative units versus watersheds) further impeding a unified system-level picture. Jointly developing models and integrated data compendia, with a broad range of thematic data sets that are spatially and temporally harmonized, will allow cross-disciplinary research to be more easily executed.

SYNTHESIS FINDING 6. Science conclusions and uncertainties require better translation into information for policymakers. Expected change in the Arctic system will be complex, multifaceted and multiscale. Decision-makers and managers must therefore recognize that a particular action that targets one scale may not be adequate—and in some cases detrimental—at another. Uncertainties in scientific knowledge can be compounded when moving across scales, yet these uncertainties have rarely been quantified or conveyed to decision-makers. Fostering a dialogue through which the decision-making community clearly articulates the space and time domains over which they require policy-actionable scientific information and through which the science community can assess their readiness to provide this knowledge will constitute an important step forward in the effective transfer of science to policy.

1. INTRODUCTION

The scientific community today faces mounting demands to provide reliable and policy-actionable information on the state and trajectory of change across the Arctic system. Understanding the decline of sea ice, polar bear and other wildlife population changes, Greenland ice sheet dynamics, fluctuations in terrestrial carbon reservoirs, and environmental impacts on Arctic social systems requires a coherent and comprehensive view of regional and pan-Arctic dynamics as well as linkages to the lower-latitudes.

The scientific community has invested heavily in the intellectual, experimental, and logistical infrastructure that supports researchers focused on in situ and local place-based studies. Although these investments are a critically important foundation for the scientific understanding of the Arctic, there exists a growing number of techniques and approaches that enable researchers to observe, simulate, and analyze trends over much larger spatial scales, including the full pan-Arctic. At the same time, Arctic scientists have yet to develop a coherent way of tackling such fundamental questions like: *Are the measurements that plant physiologists make at the leaf, plant, or plot scale relevant across the entire Arctic domain?* or the arguably more complicated question: *At what spatial and temporal scales do the signatures of climate change and variability translate into impacts on land- or ocean-based food webs that in turn affect indigenous harvests?*

Relatively little research has been dedicated to the design of strategies that coherently link place-based studies with Arctic dynamics across the spectrum of scales. Each scale along this spectrum is valuable in its own right, yet the synergies across scales are not yet fully understood or appreciated. Tangible strategies to bridge the scales and to ensure a consistent quality of conclusions across different scales have not been adequately developed. As a result, we have an incomplete understanding of how dynamics observed at well-studied, local sites are ultimately transformed into the behavior of the full Arctic system. *How can we create a coherent picture of the system and its dynamics across all relevant scales?* The ability to answer to this question requires improvement of scaling approaches for specific aspects of the system being evaluated by each community of researchers.

The need for research to improve scaling approaches in the Arctic is the central focus of this U.S. Arctic Research Commission report. Although scaling issues are hardly unique to the Arctic sciences, by addressing scaling in an Arctic context, the Commission hopes to shed light on an approach to research that merits an elevated level of attention within federal agencies. A review of the state of the art in scaling across some important research themes is timely, especially in light of elevated interest in the Arctic as evidenced by recent agency investments in the 2007–2009 International Polar Year and Arctic Observing Network.

The principal aims of this report are to:

- Review approaches to scaling across a variety of disciplines and applications
- Identify opportunities for the use of scaling to improve our capacity to understand the state and trajectory of the Arctic system
- Articulate the role of scaling in accommodating the needs of the environmental policy and management communities for scientifically sound information
- Develop a Call-to-Research around which the research community and U.S. federal agencies can identify promising new arenas of scientific enterprise

The purpose of this report is not to conduct scaling studies per se, but instead to identify research needs, challenges, and opportunities associated with the role of scaling in the Arctic research agenda. This goal will be achieved by providing some key examples drawn from several thematic areas. The report is strategic in nature, and is illustrative as opposed to being fully comprehensive. In this context, the targeted audiences are scientists, practitioners, and, importantly, agency program managers within the auspices of the Interagency Arctic Research Policy Committee (IARPC),

the State of Alaska, and others interested in how integrative scaling research can improve science that supports policy and public information about the Arctic.

This report is structured to be both informative yet also practical, given the wide-ranging set of issues that will be presented. To this end, it begins with an overview of research challenges across major thematic arenas, with several illustrations on the use of scaling to forward the research agenda in particular disciplines. Both biogeophysical and human dimension issues are discussed. There is then a treatment of several synthesis issues drawn from these examples, indicating how scaling can be used to formulate an improved vision of the state and trajectory of the Arctic system, turning attention to research that is more interdisciplinary in nature. The report next addresses scaling issues in the domain of societally important applications. The report ends with a synthesis of key findings, followed by a set of specific recommendations for research, targeted at the IARPC agencies.

For those interested, **Appendix 1** presents a more technical background on scaling.

2. SCALING CHALLENGES WITHIN ARCTIC SCIENCE
A DISCIPLINARY PERSPECTIVE

2.1. INTRODUCTION

With several new and important scientific studies, major international assessments, and high-profile media reports documenting dramatic environmental changes, it is no surprise that the Arctic continues to command the attention of scientists, policymakers, and the public. Although the paleographic record demonstrates the region to be dynamic and susceptible to major climatic shifts, there is growing evidence that today the Arctic's environment is changing at an unprecedented rate by modern standards—as evidenced by broad-scale increases in air temperature, rapid gains/losses in lake area associated with permafrost degradation, major "greening" and geographic shifts in vegetation, reductions in sea ice cover, melting of ice sheets and smaller glaciers, heating and loss of permafrost, changing river flows, lengthened ice-free period in lake and rivers, and reduction in snow cover. There is also concern about how recently observed increases in freshwater supply to the Arctic Ocean and the North Atlantic could reduce thermohaline circulation, with potentially global-scale climate change consequences.

Although a fundamental feature of these changes is their coherence, the driving mechanisms and ultimate effects of these many changes are still poorly understood. The transformation of the pan-Arctic to a seasonally ice-free state that is likely to persist for centuries is an emerging consensus view. The consequences of these dramatic changes to the Arctic and global climate systems have thus become critical problems requiring further investigation.

Arctic research increasingly requires interactions across traditional disciplines and must address issues that are not necessarily driven by curiosity-based science. The overall demand for knowledge is often driven by policy imperatives. **Section 3**, which is dedicated to interdisciplinary discussions, highlights feedbacks among the disciplines and provides examples. Here, we focus on advances made within the traditional disciplines through which the Arctic has been examined. As will be demonstrated below, these disciplinary boundaries and approaches are not absolute, and are increasingly giving way to the new requirements of Arctic systems thinking, which focus fundamentally on the issue of how the component parts of the Arctic—physical, chemical, biological, and human—are united and produce behaviors that emerge from their interactions.

This section of the report is divided into three main parts: (1) the physical domain, composed of the atmosphere, cryosphere, land-based permafrost and hydrologic systems, and ocean; (2) marine, terrestrial, and freshwater biology and ecosystems; and (3) major scaling issues drawn from the research on human systems.

2.2. PHYSICAL SYSTEMS

2.2.1. Weather and Climate Prediction

RECOMMENDATIONS

- *Optimize observational programs and process studies to collect data that directly address the needs of Arctic weather and climate modelers.*
- *Refine remote-sensing and other strategies that upscale in situ point measurements, providing key weather and climate model parameters that can be applied over the full Arctic spatial domain.*
- *Build high-resolution GIS infrastructure and databases of variables (e.g., vegetation, soil properties, topography, slope orientation) to help downscale coarse-resolution climate model outputs onto the land mass through dynamical and statistical approaches.*
- *Unite upscaling and downscaling methodologies to ensure the appropriate "handshakes" across subdomains of Arctic weather and climate models that depict land, ocean, and atmospheric interfaces.*

SCIENCE CONTEXT

Weather and climate predictions are vital to understanding the Arctic Earth system and to planning human activities over a range of temporal scales. In the scientific realm, the Arctic is like much of the rest of the planet. It comprises atmosphere, land, and oceanic components with their characteristic dynamics and storage capacities for energy, water, and constituents, with characteristic spatial-temporal domains of key processes (**Figure 2.1**). However, as a relatively small, well-contained, coupled air-land-ocean system with sharp seasonal contrasts in energy flows and phase changes of water, the Arctic serves as an important testing ground for developments in coupled modeling. Simulating the exchange of numerical information or "handshakes" of component models across the major domains (air-land-ocean), each with their unique time constants at their interfaces (e.g., air masses flowing over near-stationary, though not immobile, sea ice), have proven difficult to firmly establish due to numerical incongruities. Further, establishing strategies that make the best use of point-scale measurements from weather stations or experimental instruments at process study sites, and merging these data sets with satellite remote sensing covering the entire pan-Arctic domain, has yet to be worked out.

On the societal front, short-term weather forecasts are vital to transportation, many outdoor activities, and, in the case of severe weather, human safety and the protection of property. At monthly to seasonal time scales, the potential benefits of climate forecasts for planning in the industrial and commercial sectors are substantial. At decadal and longer time scales, robust climate forecasts would be highly valuable for improved understanding of Arctic climate change trajectories and thus design strategies for societal adaptation in the Arctic and elsewhere. A changing climate will almost certainly bring consequential changes in high-latitude weather. Temperature and precipitation extremes will change with climate, and these extremes will impact humans and ecosystems. However, forecasts of extreme weather events and a changing climate will be effective only if they are sufficiently site-specific in ways that enable planning and preparation on the local jurisdictional scale. The scale challenge to the Arctic weather and climate science community is thus substantial, spanning many spatial and temporal scales depending on the scientific question or application need.

SCALING ISSUE

Weather and climate dynamics span an enormous range of physical processes, and spatial and temporal scales (**Figure 2.1**). Weather and climate predictions are based largely on models that divide the atmosphere (and ocean, land, and ice) into grid cells of finite volume. Typical horizontal dimensions of atmospheric grid cells range from about 10 km in regional weather prediction models to 100–200 km in global climate models. Other model components, such as those depicting the ocean and land surfaces, are sometimes divided into smaller grid cells when sufficient data exist and when experience shows that finer-scale variability exerts an impact on model fidelity. The corresponding variables assigned to each grid cell still represent averages over finite volumes or areas rather than point values.

Given user requirements for local rather than broad-area forecasts, there is a need for models to account for sharp local variations. In coastal areas, for example, steep gradients of key variables can lead to large differences in weather (including temperature, the presence or absence of precipitation, precipitation type, cloudiness, winds) and climate. Another example is when mountain ranges—known to control the spatial distribution and intensity of precipitation due to variations in elevation, wind direction, and atmospheric water vapor—are depicted in more detail from high-resolution digital topographic data. Such elevation differences cannot be resolved by a model with 10–100 km resolution, and the grid-cell average of weather variables can represent a seriously deficient forecast of weather for a particular point within a grid cell. Conversely, the finite size of grid cells and the corresponding reliance on grid-cell averages makes it necessary to parameterize processes that occur on scales finer than the size of a model's grid cell in order to make sufficiently robust calculations regarding atmospheric dynamics. The methods to make these so-called *upscaling* and *downscaling* computations continue to evolve.

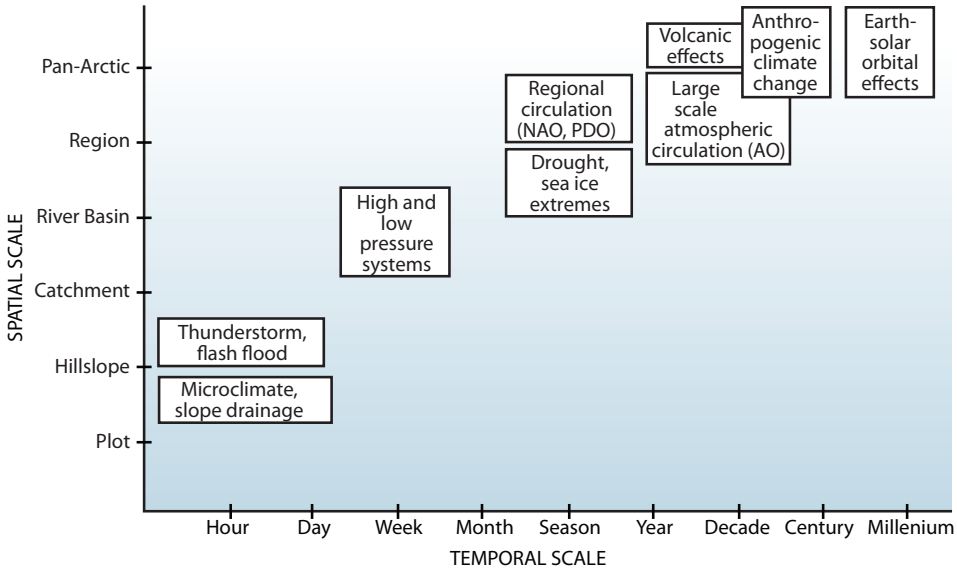


Figure 2.1. Spatial and temporal scales related to weather and climate dynamics. NAO = North Atlantic Oscillation. PDO = Pacific Decadal Oscillation. AO = Arctic Oscillation.

Climate and weather models maintain feedbacks across different domains, such that a calculation on the land surface has an implication for atmospheric physics, which then applies a control over the future state of the land mass. The challenge is to maintain mass and physical process consistency in this bi-directional context. Imagine the upscaling-downscaling challenge as a conversation between two people. The importance of a common language becomes immediately apparent.

Model Parameterizations and Upscaling

The essence of model parameterization is the effective use of one or more numerical constants that serve as input into a simulation able to capture the effect of a small-scale process without the need for explicitly simulating all of the subsidiary physical dynamics. For example, laboratory or small plot field measurements of the strength of plant leaves to control the evapotranspiration process are used to construct the land surface parameter known as stomatal resistance. In grid-based models, the grid-cell average of the effects of the process is determined by combining (1) grid-cell means of variables computed and carried forward in time by the model and (2) the parameters that are prescribed a priori (ideally on the basis of the experimental data or field measurements). Other examples of processes that are parameterized in weather and climate prediction models are turbulent mixing, radiative transfer, and cloud microphysical processes—all of which are essentially molecular-scale processes but have to sensibly be depicted (i.e., scaled) across a more macroscale domain. Given the tremendous number of molecules in a grid cell of even a fine-resolution atmospheric model (~ 10 km × 10 km × 100 m), it will never be feasible to formulate explicitly the molecular interactions that underlie these processes. However, it does become relevant to ask how experimental values can be used to construct effective parameters that can be readily absorbed into weather and climate simulations.

In ocean models, the parameterization of mixing is crucial to the evolution of temperature and salinity fields. Sea ice models often use parameterizations that treat the fraction of leads, the extent of ridging, and the associated

ice thickness distribution. In terrestrial models, evapotranspiration rate is an example of a critical variable that is parameterized. The importance of the synergy between modeling and observational studies in the Arctic land-atmosphere boundary has long been recognized, although progress has been slow. Carefully designed observational/field programs and process studies targeted at modelers' needs will provide the data to more precisely define model parameters. Remote sensing has a particularly important role to play in this *upscaling*, insofar as plot-level information can adhere to categories used by remote-sensing experts who generate maps of surface conditions that are often time-varying. For example, the reflectivity of different surfaces (e.g., bare tundra vs. snow, open ocean vs. sea ice) has been shown to yield important impacts on atmosphere-surface fluxes and site-specific values can be applied to the shifting mosaic of surface types over much broader domains monitored from space.

There are nevertheless difficulties and uncertainties associated with remote-sensing data, directly linked to the scaling issue. All satellite instruments have temporal and spatial resolution tradeoffs and require ongoing and complex calibration against field data. These data are often at mismatched scales (e.g., calibrating MODIS NDVI [a vegetation "greenness" index at ~ 1 km^2] against field-based measurements of LAI [leaf-area indices at ~ 1 m^2]). The use of classification schemes for land surfaces often ignores the fact that there is a continuum of variation, for example, within a single tundra land surface class. These variations can have significant impacts on the depiction of processes. Tundra LAI can vary by an order of magnitude, and in models dependent on calculations of evapotranspiration losses from the land surface to atmosphere, substantial biases can arise.

Approaches to Downscaling

Although parameterization captures the *upscaling* of processes whose aggregate effects are important for predicting system-level behaviors, *downscaling* seeks to "spatialize" the computed, aggregate means over a grid cell into a form that could be useful in many scientific and practical applications. This downscaling is critical, for example, in capturing better the two-way interaction of coupled, dynamic models. *Downscaling* is also useful where climate model outputs drive so-called "stand-alone models," for example, providing temperature or precipitation drivers for a permafrost-hydrology model that later could be used in an economic impacts analysis of melting Arctic tundra.

The two basic approaches to downscaling are *dynamical* and *statistical*. There is also a *combined approach*.

Dynamical downscaling is based on using a high-resolution regional model nested within (or driven by) a coarse-resolution, typically global domain model, which in turn provides time-varying boundary conditions. The high-resolution model then makes its calculations over its domain, but at each computational time step moves some of its predictions across the coarse-scale boundary and at the same time gets new information from the coarse-scale model. Passing information on wind energy fields would be one concrete example. Several levels of nesting can be used to achieve very high resolution (< 1 km). Such modules may even be placed in a coarse-resolution model's grid cell to achieve ultra-fine resolution over a small area. There are tradeoffs involving the use of such an approach. On the one hand, the higher the resolution, the better the depiction of the physical domain. Indeed, certain processes like the dynamics of the atmosphere's water cycle can only be explicitly treated when depicted at higher resolutions. Yet, with every reduction in area or volume, great computational demands—and substantially increased run time—are placed on the modeling system, and for this reason we do not today have many high-resolution global models, but many more of the nested variety.

Statistical downscaling is based on—as the name implies—statistical algorithms, like multiple regression equations, which relate model-computed quantities to observational data. This approach, which generally requires a priori knowledge of a system's behavior in order to select candidate predictors, is used in weather forecasting, where the term "model output statistics" (MOS) describes the products. For example, a model's grid-cell temperature can be used as a single predictor of temperature at a specific location, building a statistical connection to temperature data from a weather station, but can also be used in conjunction with other model variables such as wind, humidity, and cloud cover from the same grid cell and/or from upstream grid cells to get a more accurate downscaled prediction. The success of the MOS approach, which may

be viewed as a statistical enhancement of raw model output, has made it one of the staples of the weather prediction enterprise generally. There are few published examples of the use of this downscaling approach in Arctic climate applications, though it has been demonstrated successfully through algorithms targeting Svalbard and Norway.

The third approach to *downscaling* involves a fusion of coarse-resolution model output and higher-resolution information. For example, the so-called *topoclimate* algorithms use climate and weather model outputs together with high-resolution topographic information and assumed (or model-derived) lapse rates to construct high-resolution fields of temperature and precipitation. One can start with observational data from surface networks, which provide the values that are interpolated and fit to the topography of the high-resolution grid. The PRISM database is one such example available for the United States, including Alaska. The PRISM database includes surface air temperatures at 1–2 km resolution. The left and right panels of **Figure 2.2** are examples of PRISM-derived temperatures. Ongoing research activities use such an approach to obtain high-resolution projections of climate by superimposing projected changes from global climate models onto the high-resolution climatologies (e.g., PRISM) of recent decades. The raw model output prior to downscaling has the excessively smooth character shown in **Figure 2.2 (center)**.

Another combination strategy for constraining downscaled, coarse-resolution model predictions uses means and variances evaluated from (1) daily or monthly monitoring station data and (2) corresponding climate model outputs. If the normalized anomalies of the model output are rescaled using the means and standard deviations of the station data, one obtains daily (or monthly) values of a particular variable. These time series can be constructed to depict future scenarios, providing temporally detailed information about extremes and temporal changes thereof. The usefulness of this approach depends on the validity of the assumption that the statistical distributions of the variables do not change over time. In recent uses of this approach (e.g., for the 2008 U.S. National Climate Assessment), Gaussian and gamma statistical distributions were used for monthly temperature and precipitation, respectively. In all of these approaches, should the downscaling misrepresent the probability density function of, say, temperature across a landscape, then any nonlinear functions of temperature will be incorrectly modeled. Statistical analyses like Kriging can provide estimates of uncertainty by exploiting information on the space-time covariances of error.

WHAT IS REQUIRED FOR PROGRESS

- *Optimize observational programs and process studies to collect data that directly address the needs of Arctic weather and climate modelers.* Field studies are critical to quantifying and understanding land-surface and ocean-surface boundary dynamics. In the end, these studies yield information about a particular category of interface, and in some instances, a particular site. It is therefore essential that these experiments be designed to

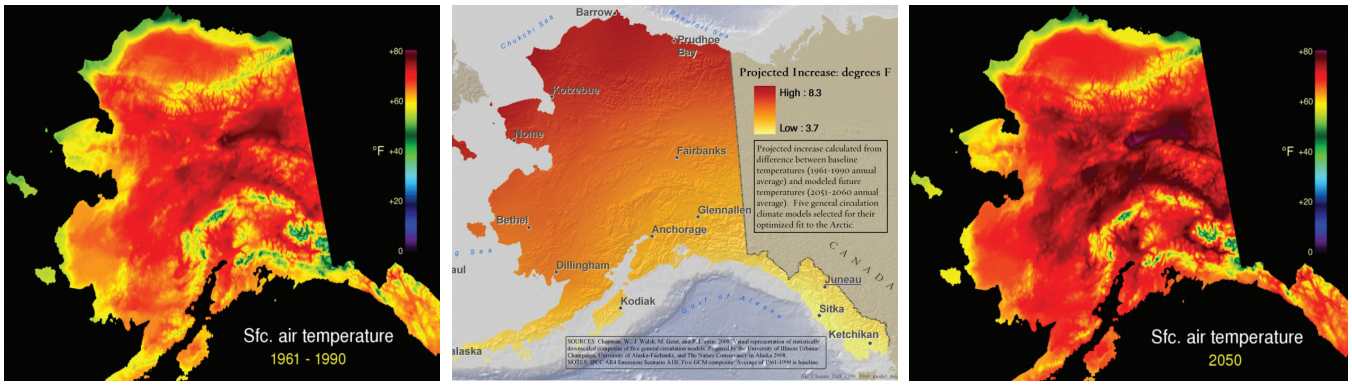


Figure 2.2. *Left:* Climatological average daily maximum temperatures for July 1961–1990. Reds represent values of 15–25°C (60–77°F), blues and greens represent values of 5–10°C (40–50°F). Temperatures are from the PRISM database (Daly et al., 2002). *Center:* Projected changes by 2040–2060 of surface air temperatures for winter in the A1B emission scenario used by the IPCC. Changes are composited over 20 IPCC models and range from about 3°F (yellow) to about 7°F (red). *Right:* Superposition of left and center panels, showing high-resolution projection for 2050. The maps demonstrate a combination technique to reconcile information at two different scales.

maximize their utility and generality in providing not only parameters for weather and climate models, but also validation data sets.

- *Refine remote-sensing and other strategies that upscale in situ point measurements, providing key weather and climate model parameters that can be applied over the full Arctic spatial domain.* Synoptic and repeated views of the pan-Arctic are afforded by a constellation of polar-orbiting satellites. These data provide calibration, validation, and operational ingestion of key land and ocean surface variables needed by atmospheric models, and provide additional and important quantitative information to improve model fidelity.
- *Build high-resolution GIS infrastructure and databases of variables (e.g., vegetation, soil properties, topography, slope orientation) to help downscale coarse-resolution climate model outputs onto the land mass through dynamical and statistical approaches.* Downscaling requires subsidiary geospatial data sets that can be used to better "spatialize" the otherwise coarse-scale outputs that characterize the current generation of climate models. A community-designed, cyber-enabled infrastructure and database resource is recommended.
- *Unite upscaling and downscaling methodologies to ensure the appropriate "handshakes" across subdomains of Arctic weather and climate models that depict land, ocean, and atmospheric interfaces.* Because of strong links in the dynamics of major components of the Arctic Earth system, upscaling and downscaling are closely interconnected, and thus a coordinated exploration of the approaches should yield advances in the manner in which future models are configured and linked to observational data programs.

2.2.2. Glaciers, Ice Caps, and Continental Ice Sheets

RECOMMENDATIONS

- *For ice sheets, encourage detailed process studies of the "throttle points" and key interfaces with potential to control broad-scale dynamics, like those between ice and ocean or lake outlets.*
- *For glaciers and ice caps, institute a systematic pan-Arctic inventory of key characteristics to enable systematic extrapolations.*
- *For ice sheets, ice caps, and glaciers, develop and execute a monitoring strategy to identify representative sampling targets that can be used to infer the surface water and energy balances plus internal dynamics of these cryospheric elements as a whole.*
- *Support studies that unite modeling and monitoring as the essential building blocks for understanding the temporal dynamics of these systems, including their placement into broader paleo/historical context.*

SCIENCE CONTEXT

Arctic glaciers, ice caps, and ice sheets (see **Box 2.1**) are a critical component of the Earth system. They store enormous quantities of water in solid form, serving as major buffers for heat exchange with the atmosphere. They are also important as great reflectors of incoming solar radiation and thus are an important controlling factor in contemporary and future climate change. From a societal perspective, they become critical primarily due to their potential contributions to sea level (**Table 2.1**). Unlike floating sea ice, the melting of which would have a negligible effect on sea level, melting of Arctic land ice has the potential to raise sea level by more than 7 m, placing in peril major portions of the global coastal zone, where a substantial fraction of the world's population resides and through which much of the globalized world's economic productivity passes. The Intergovernmental Panel on Climate Change (IPCC) has estimated that sea level will rise in the coming century by 0.18–0.59 m over the coming century, with a large contribution from shrinking ice sheets, but because the models used do not capture rapid dynamic processes adequately and the potential for ice sheet instability, the IPCC indicates that sea level rise could be substantially higher. Although glaciers and ice caps have far less potential to raise sea level than the Greenland and Antarctic ice sheets, their current contributions are today greater and may continue to be so through the coming century.

The importance of glaciers and ice sheets is underscored by their sensitivity to small changes in climate. Over the last decade, there has been increasing evidence that the disappearance of these ice masses is accelerating. For the Greenland ice sheet, which was considered until only the last decade to be a fundamentally frozen environment, we are seeing evidence that it is rapidly transforming

BOX 2.1. GLACIERS, ICE CAPS, AND ICE SHEETS

Glaciers, ice caps, and ice sheets are elements of the cryosphere that capture the essence of multiple scales. Their primary distinguishing features are size and shape. These ice features also are distinguished by scale-dependent dynamics, with glaciers and ice caps showing active dynamics today that contribute to sea level rise, and the ice sheets having more inertia but unknown thresholds.

- Glaciers are:
  - Flowing rivers of ice that are often much longer than they are wide
  - Potentially tens of kilometers long and several kilometers wide, but most much smaller
- Ice caps:
  - Fall in between ice sheets and glaciers, with scales on the order of hundreds to thousands of square kilometers
  - Exhibit some impact on their local climate and Earth deformation
- Ice sheets are:
  - Millions of square kilometers in area, several kilometers thick
  - Strongly influence their regional climate
  - Substantially deform the earth on which they rest through their weight

Ice caps and ice sheets also contain outlet glaciers, which, as their name implies, exhibit glacier-like characteristics, but are fed by the large reservoirs of ice contained in the ice caps and ice sheets.

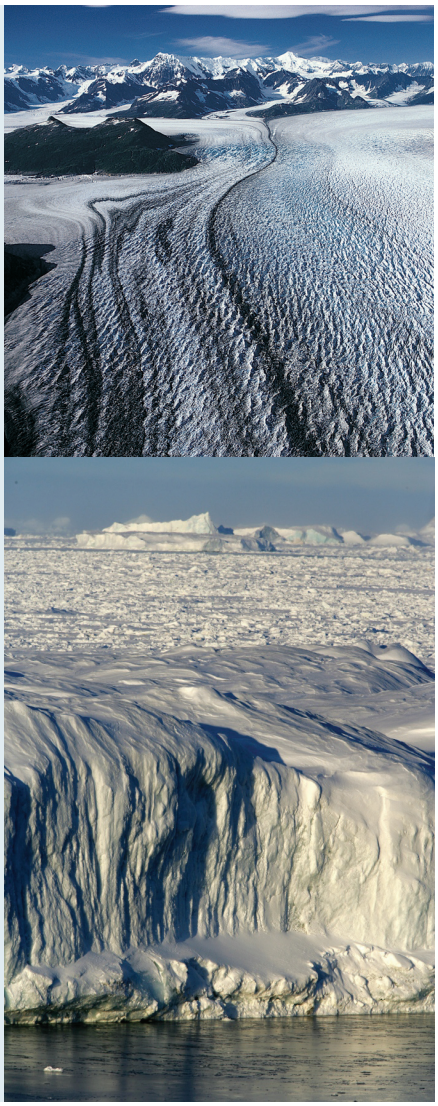


Table 2.1: Sea level equivalent of major land-ice masses.

Land-Ice Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Potential Sea Level Rise (m)
Glaciers and Ice Caps*	0.51–0.54	0.05–0.13	0.15–0.37
Greenland Ice Sheet	1.7	2.9	7.3
Antarctic Ice Sheets	12.3	24.7	56.6

*Does not include the small glaciers and ice caps that surround the Greenland and Antarctic ice sheets

from a cryospheric element of the Arctic system into a dynamic hydrologic feature that is increasingly characterized by its flows of liquid water. Issues abound with respect to the entry of freshwater into the Greenland and Nordic seas where important zones of convective deep Atlantic water exist.

THE SCALING ISSUE

Figure 2.3 shows the various scales of processes for the different types of land ice masses. They span a tremendous range of the space/time continuum. The scaling challenges associated with understanding glacier and ice cap behavior are, by their very nature, more "local," and the implications of their changing dynamics on sea level rise are different than for ice sheets, which represent a more spatially contiguous mass of ice with continental-scale climate, geological, and cryospheric dynamics. For glaciers and ice caps, of which there are over 200,000 worldwide, the major spatial scaling challenge is understanding the behavior of large glacier systems from the sampling of a few. Individual glaciers

are not of much consequence to sea level rise. However, consistent behavior across *systems* of glaciers are detectable and have been found to be substantial, as evidenced by the large sea level contributions from melting Alaskan glaciers, Canadian ice caps, and Patagonian ice fields, further enhanced by wastage of glaciers at lower latitudes worldwide. For ice sheets, the challenge is more along the lines of relating local processes—particularly at the ice/ocean interface of outlet glaciers—to large-scale behavior as it relates to total ice sheet mass balance and ice sheet stability. Glacier and ice sheet behavior is a manifestation of processes that occur across the full spectrum of temporal scales and legacy effects are apparent. The convolution of these processes makes unraveling the temporal aspects difficult at best.

The Greenland Ice Sheet

The primary scaling consideration for the Greenland ice sheet is deciphering the coupling between local processes or "throttle points" and the affected ice sheet's drainage basin. The greatest challenges are related to ice sheet dynamic processes, particularly, understanding how the interactions among floating ice, grounded ice, and seawater at the marine-terminating outlet glaciers influence the ice sheets and the smaller drainage basins that control their discharge. Outlet glaciers are on the order of a few kilometers to a few tens of kilometers wide and long, yet collectively may be critical in controlling the dynamics of an ice sheet that is on the order of thousands of kilometers in length. It is at this interface between ice and water, where change in backpressure can occur rapidly with the disappearance of floating ice. The effects of those changes propagate well up and into the ice sheet, impacting overall ice sheet balance through enhanced discharge.

A further scaling consideration related to accelerated ice flow is the similarities and differences among outlet glaciers. Each outlet glacier, where dynamic processes dominate the local balance, has its own unique dynamic characteristics. It is important to understand how representative (or not) one glacier may be of others that are similar (or different), as we try to infer large-scale behavior from local measurements. Satellite observations are crucial in this area, as they can enable the monitoring of unique dynamic processes over nearly all of the outlet glaciers. However, relating these observations to the detailed mechanisms that control flow requires comprehensive measurements on, within, beneath, and around these glaciers and their floating tongues. In this sense, the scaling challenge is similar to that of alpine glaciers: relating the knowledge we obtain in a few to the characteristics of an entire system.

The impact of meltwater penetration, often very localized, on overall ice sheet mass balance is poorly understood. It has been demonstrated that melt ponds on the Greenland ice sheet drain very rapidly and cause seasonal acceleration in ice flow. But, the spatial scales of this acceleration are not well known. Thus, it is not now clear whether 100 km of ice moves in a slab fashion or whether there is local convergence or divergence of the ice flow, limiting the impact on overall balance. If it is the latter, then the key consideration becomes over what scales and how it affects ice sheet stability. As with outlet glaciers, data remain limited, and models are not yet equipped to account for this phenomenon.

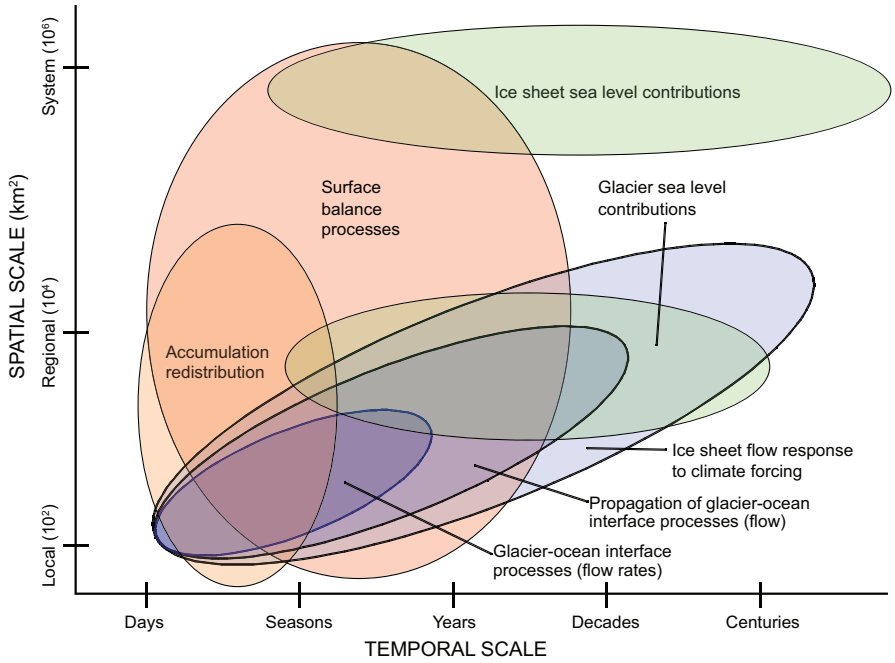


Figure 2.3. Spatial and temporal scales on which glacier, ice cap, and ice sheet processes operate.

Many questions thus remain unanswered with regard to how various processes affect overall ice sheet mass balance, and these processes are heavily linked to issues of scale. *How rapidly and far do the effects of meltwater penetration propagate into the ice? What governs the rate and magnitude of that propagation? How long does it take ice sheets and outlet glaciers to respond to new boundary conditions following floating ice breakup? How vulnerable are ice sheets to rapid loss by this mechanism?* The major challenges to answering such questions stem from the paucity of data on ice sheet bottom topography in the vicinity of outlet glaciers, floating ice thickness, grounding line processes, ocean temperatures beneath floating ice, and other variables. However, as more data are acquired, careful attention needs to be paid to the temporal and spatial scales over which these processes act. Research is needed in this area so that models designed to predict the magnitude and rate of sea level contribution from the ice sheets in the face of these potential dynamic instabilities can operate on several scales.

Finally, surface balance processes present a somewhat different sort of scaling challenge than the nonlinear, potentially unstable, dynamic processes. The issues are not so much coupling of the processes, but rather understanding the extent to which microscale measurements represent macroscale processes. Because we rely on point measurements of surface processes that are spaced hundreds of kilometers apart to calibrate and validate models and satellite data, it is critical that we understand whether the local processes measured in situ are representative of broader domains. Surface energy and mass exchanges are governed by small-scale (millimeters to meters) roughness, while surface accumulation is heavily influenced by topography and wind redistribution on scales ranging from centimeters to kilometers. Knowledge of the spatial variability and the dependence of surface balance on that variability is an important area requiring further research.

Glaciers and Ice Caps

To better understand the impact of glacier and ice cap changes we need to: (1) be able to assess the overall behavior of a glacier based on information acquired at a few locations or across a few transects, and (2) extrapolate information from a limited number of glaciers to larger areas. It is instructive to categorize changes due to surface mass balance and dynamics separately, and to consider short- and long-term changes (i.e., the response time of a typical glacier, which is on the order of several decades).

Considerable evidence suggests that for short-term changes, surface mass balance can be characterized for a region from a limited number of benchmark glaciers or weather station measurements. Scaling from remote-sensing observations, such as airborne laser altimetry or satellite-based NASA Gravity Recovery and Climate Experiment (GRACE) measurements on regional scales (tens of kilometers) to the microscale, can allow us to determine which benchmark glacier or weather stations (coupled to a mass balance model) are most representative of a region; or, if existing data sets are not representative, what adjustments need to be made to make such data sets representative; or, whether entirely new benchmark data sets are needed. One example of successful benchmark glacier identification exists in Norway, where measurements at a single stake on a single glacier represent changes on all 12 glaciers across a region. The task is to find similarly representative locations in other regions. An important part of determining which glaciers can serve as benchmarks, and how those glaciers need to be sampled, is determining the spatial structure of surface mass balance, in particular, the accumulation component, which tends to have high spatial variability.

In addition to these surface balance considerations, which are tied to climatic processes, there are the nonlinear glacier changes related to the dynamics of marine or lake-terminating glaciers that do not appear to follow climatic cycles. These changes can affect regional calculations over all time scales, but only for regions with these types of glaciers. As such, we need to categorize glaciers as being *land-terminating* or *water-terminating* so that climatic versus nonclimatic processes can be appropriately dealt with. Moreover, we need to identify the phase of a tidewater glacier cycle (advance vs. retreat) from satellite imagery, and treat it separately in scaling analysis. There may be simple ways to scale elevation change profiles between retreating tidewater glaciers, but more work is needed.

Finally, a major uncertainty in assessing worldwide glacier contributions to sea level is the limited knowledge of glacier areas. Mapping of glaciers has neither been thorough nor systematic, and the fact that many glaciers are

changing so rapidly increases the challenge. Ultimately, we cannot effectively scale any condition or parameter if we do not know the area to which we are scaling. For this reason, *a priority needs to be a systematic mapping of glacier areas throughout the world*.

TEMPORAL CONSIDERATIONS

The remaining scaling challenge for glaciers and ice sheets is that of time, more specifically, placing recent change into broader context. Our ability to measure glacier and ice sheet processes on any kind of meaningful scales is very recent. There are some glaciers in Europe for which records exist for hundreds of years, but for most glaciers, the records are either nonexistent or only span a few decades. For ice sheets, the ability to observe large-scale behavior has only come about in the last couple of decades with advances in satellite remote sensing. Thus, a major challenge remains in fitting the processes we are observing today into the appropriate temporal context. Ice cores hold a tremendously valuable record of past climatic conditions and associated surface mass balance conditions, but the same cannot be said for understanding flow-related processes, particularly at ice sheet margins, or processes in areas where excessive melt has contaminated the ice core records.

There are techniques for crudely estimating past ice boundaries from geological signatures, or inverting present ice characteristics and structure to determine past conditions. The former is limited, however, to areas that are currently exposed (i.e., they don't tell us about past conditions in which there was less ice), and they don't tell us much about the rates of change. The latter is limited by the amount of data available on the structural conditions within the ice. As a result, we know very little about how changes in present ice conditions relate to those of the past. For example, we do not have observational evidence to determine whether the recently reported flow acceleration in much of southern Greenland marks the beginning of a rapid decay of the ice sheet, or whether this is a process that has come and gone repeatedly through time. As we continue to improve models with the collection of more data, we will be able to understand the time scales over which dynamic changes occur, and gain a better understanding of how today's processes fit into the broader temporal context. For now, however, this major challenge remains.

WHAT IS REQUIRED FOR PROGRESS

- *For ice sheets, encourage detailed process studies of the "throttle points" and key interfaces with potential to control broad-scale dynamics, like those between ice and ocean or lake outlets.* Recent research has shown the importance of outlet glaciers, their linked drainage systems, and how far up into the ice sheet their dynamics penetrate, for example, the excursion of meltwater up into the ice sheet. Given the potential of these smaller component systems to control ice sheet dynamics over a much larger domain, they merit special attention.
- *For glaciers and ice caps, institute a systematic pan-Arctic inventory of key characteristics to enable systematic extrapolations.* Given an incomplete global picture, despite their current importance to global sea level rise, an inventory should be made immediately to provide a benchmark against which future change can be assessed. The inventory should include state variables, such as the detailed position of fronts, areas, and volumes.
- *For ice sheets, ice caps, and glaciers, develop and execute a monitoring strategy to identify representative sampling targets that can be used to infer the surface water and energy balances plus internal dynamics of these cryospheric elements as a whole.* This recommendation addresses the key challenge of searching for general behaviors from incomplete sampling, such as the outlet glaciers of the ice sheets to representative glaciers and ice caps that are emblematic of regional systems of these smaller features of the cryosphere.
- *Support studies that unite modeling and monitoring as the essential building blocks for understanding the temporal dynamics of these systems, including their placement into broader paleo/historical context.* These studies will plug a gap in current data sets and tools for understanding how representative current conditions are with respect to the past, such as for the advance/retreat cycle of tidewater glaciers.

2.2.3. Permafrost and Hydrology

RECOMMENDATIONS

- *Foster development of landscape evolution models across the Arctic, focusing on the propagation of small-scale processes to sequentially larger domains.*

- *Support work to design systematic sampling programs that can provide guidance in choosing representative sites for monitoring key parameters and variables.*
- *Improve understanding of the nature of continuous and discontinuous permafrost dynamics and the characteristic space-time domains of their change.*
- *Continue studies that explore the macroscale behavior of water fluxes, focusing on an acceleration of the hydrologic cycle.*

SCIENCE CONTEXT

Water in all of its phases –solid, liquid, and gas—is the fundamental "glue" linking virtually all aspects of the Arctic system. The importance of water distributed over the Arctic landscape is inextricably linked to the state of permafrost, that is, the perennially frozen ground that undergoes rapid change in response to seasonal temperature changes and freeze-thaw, a potentially long-term if not permanent reconditioning in response to greenhouse warming.

This landscape is central to the functioning of the pan-Arctic system as a whole, with its centrality defined by fluxes in both horizontal and vertical dimensions. For example, water and permafrost are important for storing matter and energy—snow and rainfall collects on the surface, is stored temporarily on vegetation and in soils and surface waters, but can ultimately be re-evaporated into the atmosphere. Snow is also an important control of surface energy fluxes through its high level of reflectivity to incoming solar radiation. The hydrology of hillslopes is conditioned both horizontally and vertically, with important gradients in moisture and upslope-downslope redistributions of water and constituents that help to define the patterning of vegetation. Excess water draining from Arctic terrestrial ecosystems is horizontally redistributed through groundwater movement and through stream channels, both in terms of poorly organized wetland and lake complexes in shallow gradient landscapes, and through bona fide drainage networks that in some cases coalesce into some of the world's largest river systems.

Some of these large rivers are discharging increasing amounts into the Arctic Ocean, a possible harbinger of an acceleration of the high northern water cycle, but one with unclear interpretations that could involve climate, land cover, and water engineering changes. This increasing discharge also affects global-scale ocean behavior. Several temporal and spatial scales define such interactions, but a consistent set of results from field to hemispheric scales is absent (see **Figure 2.4**).

Climate change is modifying the nature of Arctic landscapes and how they store, release, and process water (**Box 2.2**). Thermokarst topography forms as ice-rich permafrost thaws, either naturally or anthropogenically, and the ground surface subsides into the resulting voids (**Figure 2.5**). The important and dynamic processes involved in thermokarsting include thaw, ponding, surface and subsurface drainage, and surface subsidence and related erosion. These processes are capable of rapid and extensive modification of the landscape; preventing or controlling anthropogenic thermokarsting is a major challenge for northern development. Thermal degradation of ice-rich permafrost with coincident subsidence of the ground surface has recently resulted in extensive thermokarsting and creation of new water-filled surface depressions on the Beaufort Coastal Plain in northern Alaska. Analysis of aerial photography indicated that widespread ice wedge degradation had not occurred before

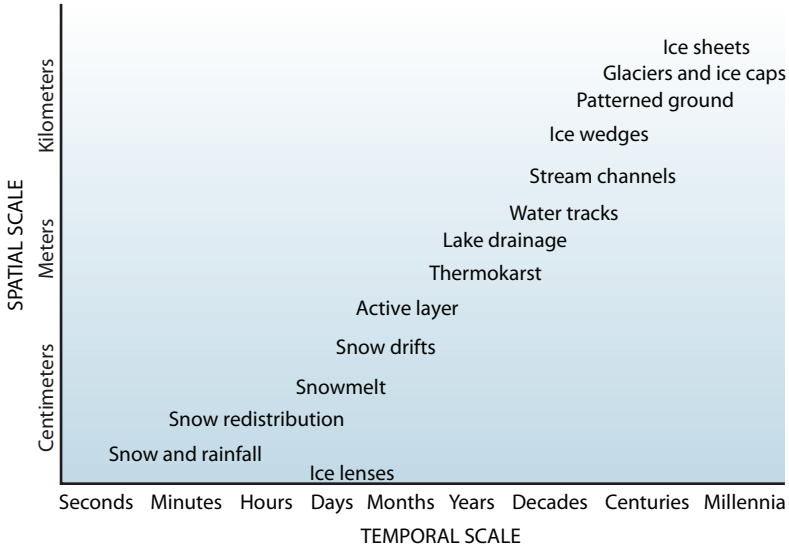


Figure 2.4. Characteristic scales of organization for hydrology, permafrost, and affiliated watershed processes.

BOX 2.2. DYNAMICS, FUNCTION, AND SCALE IN PERMAFROST-DOMINATED HYDROLOGIC SYSTEMS

Hemispheric-scale changes to climate reverberate to the microscale, exemplified well by the coupling of hydrology and permafrost. In response to some imposed disturbance, such as a tundra fire or climatic warming, massive ice permafrost may differentially thaw, creating irregular surface topography. Depressions forming on the surface soon form ponds, accelerating subsurface thaw through lower albedo (reflectivity of incoming solar radiation) and additional heat advected into the pond through runoff. In time, a talik (a layer of unfrozen soil above the permafrost and below the seasonally frozen soil) may form below such ponds as the water depth becomes greater than the amount that can refreeze during the winter. If the talik grows to a size that completely penetrates the underlying soil or connects to a subsurface layer that allows continued drainage, the pond may then begin to drain (**Figure 2.5**). In recent years, numerous studies have documented changes in the size or number of surface water bodies. The implications of these analyses are that in regions over thin permafrost (~ < 20 m), surface ponds may shrink and surface soils may become drier as the permafrost degrades. This condition depends upon regional hydrologic gradients (i.e., whether the region is a groundwater upwelling or downwelling zone). The same mechanisms that allow drying of the ponds may also cause soil drying with significant impacts to latent and sensible heat fluxes. In colder regions with thicker permafrost, as the warming proceeds, near-surface ice thaws, the land surface subsides, and new water bodies are formed.

1980. Field observations and sampling showed that ice wedge degradation has been relatively recent, as indicated by newly drowned vegetation. Despite the relatively cold average annual temperature of this northern permafrost, thermokarst was widespread on a variety of terrain conditions, but most prevalent on ice-rich centers of old drained lake basins and alluvial-marine terraces.

Figure 2.5. Shrinking ponds resulting from degradation of permafrost have been documented in Alaska, Canada, and Siberia. Drying of these ponds often accompany changes in surrounding soil moisture and vegetation, with a months-to-decades time scale.

THE SCALING ISSUE

Extrapolating field measurements or modeling results across spatial and temporal scales remains an important technical challenge, acknowledged by several major documents focusing upon research needs in the twenty-first century (e.g., The National Academies *Arctic Observing Network* report). Effectively resolving this problem will only be achieved through coordinated field studies and complementary modeling analyses targeting a range of scales. Current techniques do not effectively consider the losses in precision that are incurred as measured or simulated variables are expanded over greater and greater areas (see discussion of a similar problem in the atmospheric sciences, **Section 2.2.1**). In order to confidently validate hydrological models, predictions should be compared to field measurements from the spatial and temporal domain being simulated; however, it is only recently becoming possible to measure certain field parameters over spatial scales greater than a few meters.

Arctic landscapes are complex, and the challenge is one of understanding their structure and dynamics, which vary greatly over scale. Gradients and fronts, embodying in

many cases extremely small scales, characterize the water-permafrost system. The smallest-scale water movement in the Arctic relevant to watershed hydrology arguably is the microscopic water migration in frozen soil across a thermal gradient. Due to the tensions created in thin films of water on soil particles, liquid water will be drawn from warmer soils toward the freezing front. Depending upon the types of soil and amount of water available, ice lenses on the order of millimeters to centimeters thick can form parallel to the freezing front. These ice lenses play an important role in the hydrologic and thermal dynamics of frozen soils, influencing both heave and subsidence. Likewise, water migration toward the permafrost table during the summer months maintains an ice-rich layer of very low permeability just below the active layer (the surface layer of soil that experiences thaw every summer).

Although such processes are critical at the microscale, their dynamics can be detected using environmental sensing techniques over different scales relevant to hydrologic and permafrost dynamics in the field. Wireless communications and cheap, autonomous, networked sensors enable the development of "sensor nets" as a means to monitor landscapes over a range of scales (e.g., patch to hillslope to small watershed) for direct input to or testing against models. For still larger domains, airborne and satellite remote sensing can be used. In particular, microwave radiometer and radar data sets have been used to detect freeze-thaw signatures and the onset of runoff events in small watersheds and across the entire pan-Arctic.

Furthermore, local permafrost change propagates its impact over much broader dimensions. Permafrost, which is at least 100,000 years old in much of the Arctic, has acted to both constrain development of drainage networks and produce much of the microtopography that characterizes large areas of the Arctic. The common tussock is a decimeter-scale topographic feature that exerts scale-dependent controls on water movements across the region. Tussocks exert primary control over small-scale soil moisture variations, often being quite dry on top with standing water between the tussocks (**Figure 2.6**). During spring runoff events, when the active layer is still very thin, the rapid component of hillslope runoff occurs either as overland flow, inter-tussock flow, or as pipeflow and matrix flow in the highly organic near-surface soil. On hillslopes, water moves in circuitous routes around the tussocks until entering water tracks, or small first-order channels that quickly drain hillsides. Water tracks have a very simple structure, tending to form in parallel drainages, straight down the hillside, separated by 20 to 50 m. As permafrost warms and soil erodes, it is expected and observed that drainage networks formed of water tracks will evolve toward dendritic drainage patterns commonly observed in more temperate regions, thus changing the "rules" and scales by which these systems function.

Although water tracks are typical on hillsides, patterned ground is the dominant topographic feature in flat areas such as the coastal plain (**Figure 2.7**). The time scales of forming such polygonal patterns occurs over tens or hundreds of thousands of years. As tundra soil cools quickly during cold winters, contraction cracks appear, generally in the same location year after year. When the snow melts in the following spring, water infiltrates the cracks and quickly freezes, expanding upon freezing, and pushing the soil farther apart. As this repeats over the centuries, massive ice wedges develop into troughs bounded by ridges of soil. These intricate spider webs of channels maintain dominant control on soil moisture. Although they allow lateral water movement, their primary influence results through vertical scaling and the control on the water table. Sedge tundra typical of the coastal plain is adapted to the hydrophilic environment maintained by the low gradients and shallow water table. However, with a warmer climate, as permafrost degrades and ice wedges melt, the troughs become deeper and the depth to the water table increases, drying the

Figure 2.6. Water movement around tussocks is an important flow regime on small scales over much of the Arctic.

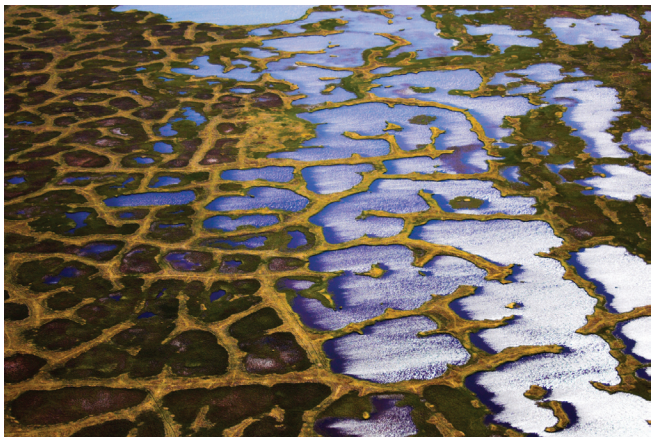


Figure 2.7. Subtle elevational differences (on the scale of centimeters to decimeters) exert the dominant control on hydrological processes of snow distribution, runoff, and soil moisture variations. These polygonal features consist of intersecting wedges of massive ice, and therefore also represent a vulnerable landform that is adversely impacted by a warming climate.

surface and drastically changing the habitable environment for vegetation. Although these processes are fundamentally local, they may exert the most important influence on regional scales, as a small change in distance to the water table may initiate broad-scale drying, which will influence regional ecosystems and the regional surface energy balance.

Hydrologic drainage patterns have major influence on the spatial distribution of soil moisture, and an increase in the number of incised channels will result in a reduction in surface area of poorly drained or wet soils. This may alter vegetation distribution and subsequently snow distribution. Digital elevation models (DEM) have allowed unprecedented investigations into the spatial arrangement of landforms in recent years, and a new suite of descriptive parameters has emerged in fluvial geomorphology (**Figure 2.8**). Foremost are the fractal dimension and the cumulative-area distribution. Several researchers have used these parameters to show that mature channel networks possess a high degree of similarity in the spatial distribution of channels, regardless of geologic control.

WHAT IS REQUIRED FOR PROGRESS

- *Foster development of landscape evolution models across the Arctic, focusing on the propagation of small-scale processes to sequentially larger domains.* Given the close connection between permafrost-hydrologic change and the response dynamics of coupled water-vegetation-geomorphological systems, models uniting these dynamics are needed over sufficiently long time domains to capture the impact of forecast climate

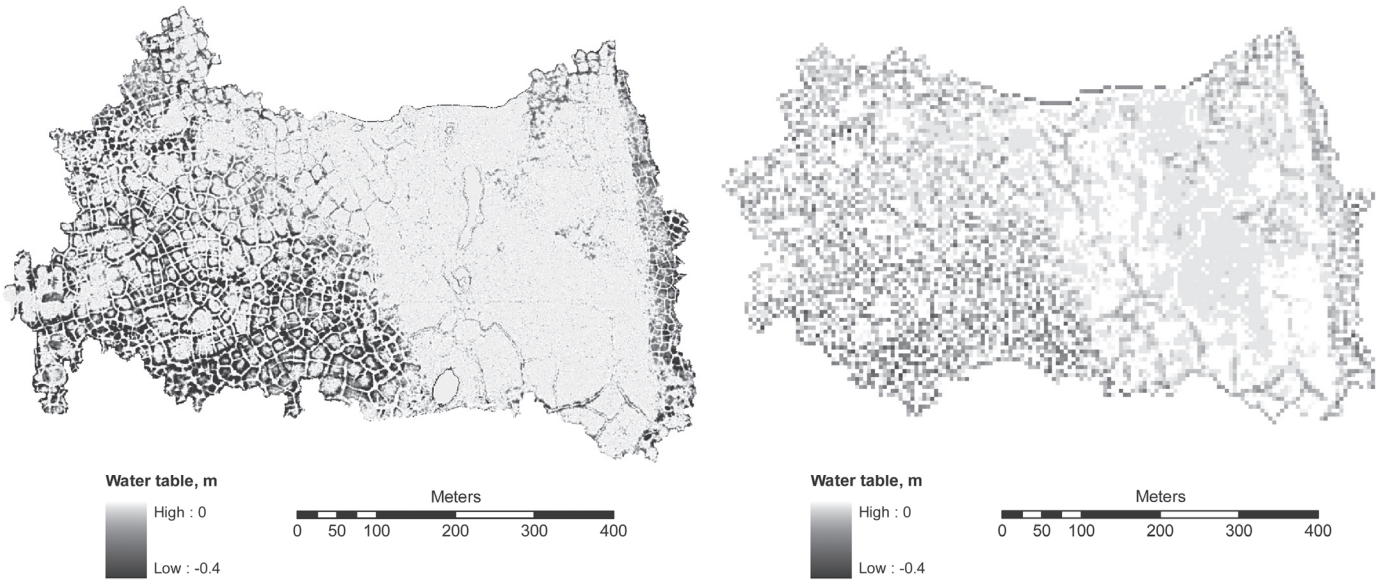


Figure 2.8. Hydrological simulations of water-table depth across a vegetated drained thaw lake basin near Barrow, Alaska, based upon contrasting horizontal DEM resolutions (1 m on left and 5 m on right). Both DEM s represent arithmetic averages of a 0.25-m pixel DEM, which was derived from airborne LIDAR measurements. The simulations were initialized with the water table at the ground surface and forced with the meteorological conditions of summer 2006. The figures represent the 75th day in the simulation. Results highlight the need to adequately treat scale in representing key landscape characteristics and processes. *(Produced by A. Liljedahl)*

change, but recognizing the importance of sufficiently treating the simulation of shorter-term dynamics (e.g., seasonal freeze-thaw).

- *Support work to design systematic sampling programs that can provide guidance in choosing representative sites for monitoring key parameters and variables.* The complexity, remoteness, and harshness of the Arctic means that deployment of field sampling stations will be finite and modest at best. The complexity of the Arctic landscape must be met with organized classification systems for landscape and permafrost types that can be used optimize field data campaigns and later map, using remote sensing, the dynamics of these landscapes.
- *Improve understanding of the nature of continuous and discontinuous permafrost dynamics and the characteristic space-time domains of their change.* Thermokarsting, and the waxing and waning of inundation in lake systems, are important hydrologic responses to warming that will change the horizontal and vertical connectivity of low-relief landscapes across the pan-Arctic. Reconciling field observations of individual sites with regional-perspectives afforded by remote sensing will be required.
- *Continue studies that explore the macroscale behavior of water fluxes, focusing on an acceleration of the hydrologic cycle.* Such studies will need to consider a host of factors that are often clearly observable for specific sites (e.g., logging, fire, permafrost degradation), but have yet to be upscaled coherently to help explain progressive increases in the discharge of large Eurasian rivers.

2.2.4. Arctic Ocean and Sea Ice

RECOMMENDATIONS

- *Create opportunities for improved understanding of the Arctic Ocean and sea ice as a coupled system, by uniting monitoring and process studies of its individual components.*
- *Support work aimed at articulating how dynamics propagate across Arctic Ocean components.*
- *Catalyze modeling studies that address contrasting space-time scales embodied by a variety of Arctic sea ice and ocean processes.*

SCIENCE CONTEXT

Recent studies have drawn attention to observed changes to the Arctic Ocean and its sea ice, the importance of regional ocean dynamics, and the implications of these Arctic-based changes on the broader global ocean and climate system. Predictions for the twenty-first century show that there are substantial changes in the form of freshwater export from the Arctic Ocean. With a severe decrease in sea ice, the total flux becomes dominated by liquid freshwater. Synthesis of results from models contributing to the *IPCC Fourth Assessment Report* documents a consistency across models in terms of an acceleration of the hydrologic cycle, expressed as increases in the fluxes of water through major elements of the system. Principal among these fluxes are increases in freshwater inputs to the ocean from net precipitation, river discharge, and sea ice melt, and an increase in liquid water storage. While the current state-of-the-art represented by these models are in qualitative agreement, it is noteworthy that the magnitude of trends and some of the basic ocean and sea ice budget terms require substantial improvement and that the treatment of key ocean dynamics and sea ice processes vary considerably across models.

Perhaps most telling is the fact that ice-free conditions in the observed contemporary record predate model predictions by decades (**Figure 2.9**). The future appears to be the present. The long-term ramifications could be profound, and it has been reasoned that the system has few if any "backstops" against the continuation of such changes. Particularly important is the so-called sea ice-albedo feedback, wherein exposed relatively dark ocean waters continue to absorb summertime incoming solar radiation, making it more difficult to reestablish sea ice during the winter months. Evidence is accumulating that the amount, thickness, and ages of sea ice (i.e., the loss of thick, multi-year ice) is moving toward a more seasonally ice-free and less-ice-dominated ocean system. Systemic change in sea ice will bear important implications on the physics, chemistry, and biology of the ocean, as well as upon indigenous livelihoods. The global economy, eager to exploit new sources of natural resources and new transportation corridors, will also become more dependent on a reconfigured Arctic Ocean system and hence the ability of scientists to forecast its future state and dynamic trajectories.

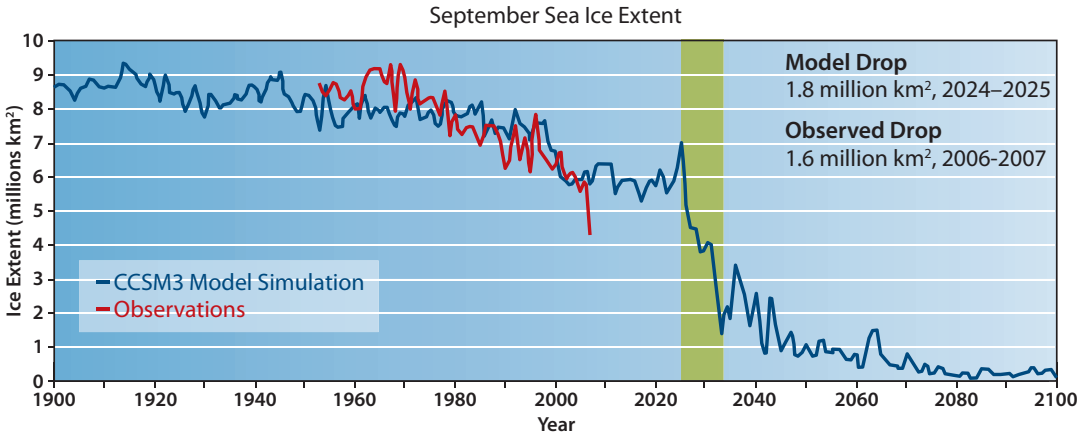


Figure 2.9. The rates of present-day loss of sea ice rival those of simulations of Arctic sea ice 20 years into the future. A possible tipping point beyond which sea ice cannot return could become a present-day reality. *(Redrawn after Holland et al., 2007).*

THE SCALING ISSUE

Ocean circulation scales are set partly by physical boundary conditions (the ocean surface and seafloor bathymetry), and partly by internal processes generated by the nonlinear equations of fluid motion. The result is that the ocean contains important dynamical features at all spatial and temporal scales, from the smallest (millimeters, seconds) to the largest (global, millennial). Processes at these different scales interact in significant yet often poorly understood ways.

The Arctic Ocean is, to first order, a "two-layer fluid," with a fresh, cold upper layer (0–300-m depth) influenced by the cold atmosphere and freshwater influx from rivers, net precipitation, and relatively fresh inflows from the North Pacific Ocean. The addition of sea ice adds a large degree of complexity. Sea ice has several roles in the ocean system, which play out across multiple scales. Sea ice acts as a cap to thermal exchanges, is an important reflector of incoming solar radiation in the summer, and acts as an energy storage and release mechanism as it undergoes seasonal changes in phase. It also interplays in a complex way with ocean currents and surface winds. Further, the Arctic seas have their own special conditions (e.g., sea ice, huge continental shelves, a nearly constant Coriolis parameter) that bear impacts on the broader ocean circulation, making for a challenging scaling environment (see **Figures 2.10 and 2.11**).

Arctic Sea Ice

Sea ice often appears self-similar across a range of geophysical scales. Low-altitude aerial photographs are visually similar to high-altitude photographs and satellite imagery. Although this is an interesting property of sea ice, for the purpose of understanding and modeling sea ice physics, there are distinct spatial and temporal scales, as well as important transitions, that are particularly relevant, based on both its internal structure and external forcing.

Figure 2.10 shows a hierarchy of scales that divides sea ice dynamic processes into floe, multi-floe, aggregate, coherent, sub-basin and seasonal scales. The rationale for identifying these scale differences is that there are, in general, distinct model formulations with particular variables and parameters used at each scale. The first significant change in sea ice behavior appears as an emergent property at the transition from the multi-floe scale to the aggregate scale, where a statistical mechanical length scale is established and sea ice can be considered a plastic continuum. A second important length scale is known as the coherent scale where the spatial and temporal scale of sea ice mechanics best match the external length scale of wind forcing. Winds on the coherent scale in turn provide nonlocal forcing to the aggregate scale. At dimensions larger than the coherent scale, spatial and temporal averaging of the external forcing occurs in the sea ice response. Understanding and modeling sea ice dynamics at each of these scales requires formulating the problem in terms of the variables and parameterizations at the next smaller scale.

The above scaling methodology relies primarily on a hierarchical approach to scientific inquiry. There are other approaches, most notably that recognize fracture mechanics as a key organizing process on all scales. This view is still compatible with the above hierarchy as the coherent scale emphasizes coupling with external forcing, rather than internal structure within the medium.

The Arctic Ocean's Surface Mixed Layer

Surface mixed layer scales (0–50-m depth) are set by interactions with the overlying atmosphere and sea ice. In particular, sea ice presents a unique boundary condition linked to a variety of scales. For example, ice formation leads to a negative buoyancy flux from brine rejection within the smallest-scale molecular sublayer at medium-scale ridge keels and leads, and in the larger scales of polynyas and seasonally ice-free areas. This process is analogous to wintertime cooling and mixed-layer destabilization in lower latitudes, except that salinity plays the dominant role in determining density at cold arctic temperatures. Moreover, subtle details of small-scale convection at the sharp boundaries of a lead may in fact create a stabilizing influence during brine rejection. Conversely, summer brings freshwater into the surface layer from a variety of sources. Rivers, essentially point sources for freshwater and heat, often reach maximum flow while the ice is still melting at the shore, leading to flooding on the ice and temporary "impoundments" of freshwater below. This influences the residence time on the shelf and exchange of freshwater with the rest of the Arctic Ocean in poorly understood ways. Sea ice meltwater may collect in leads and melt ponds during light wind conditions, only to be mixed downward during wind or melt events. The net annual effect on the ocean surface layer has been referred to as a "distillation" process wherein salt is seasonally sequestered below a fresh surface layer. The overall residence time of this uppermost layer in the Arctic Ocean is probably similar to the overlying sea ice cover (i.e., 1–10 years). A recent synthesis targeting the stocks, flows, and residency time attributes of the entire pan-Arctic water cycle demonstrated the value of such

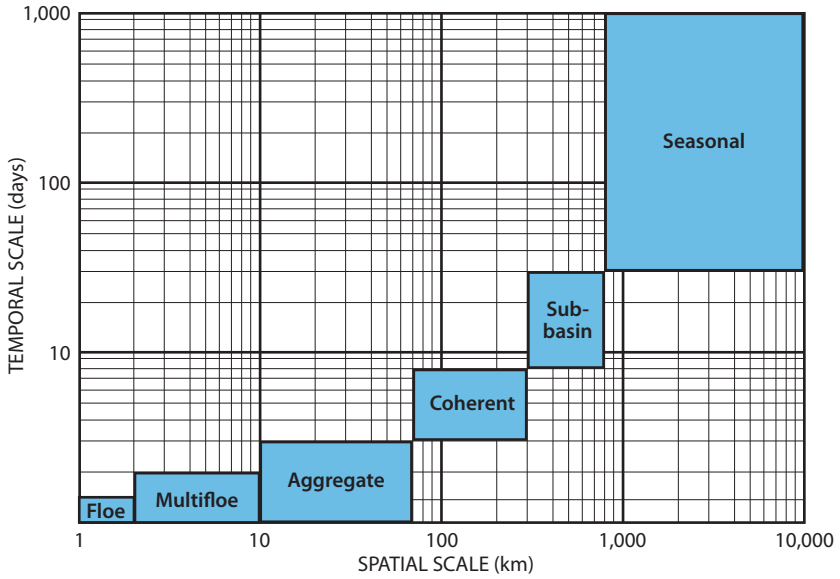


Figure 2.10. Dominant temporal and spatial scales in Arctic sea ice studies.

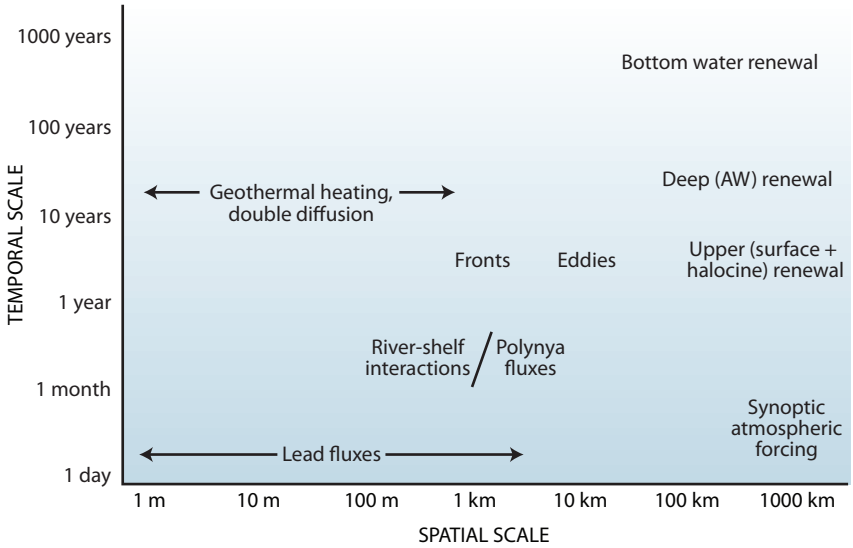


Figure 2.11. Dominant temporal and spatial scales in Arctic oceanography. AW = Atlantic Water.

integrative measures, for example, a newly recognized importance of Bering Strait inflow variations on the overall system dynamics.

The Pycnocline

Between 50 and 300 m below the sea surfaces lies the pycnocline, composed of a variety of water masses formed both on shallow shelves and within deep basins. The Arctic Ocean pycnoclines develop their characteristics by modification of Pacific Water (PW), Atlantic Water (AW), and river waters through interaction with some combination of the cold atmosphere, melting or growing sea ice, and benthic conditions on the shelves. Formation regions can be relatively small scale (e.g., a shore polynya) but by lateral intrusion into the layered pycnocline they can influence the entire Arctic Ocean and even the North Atlantic Ocean via southward currents. Cooling and/or salinization on the shelf produces dense water that forms benthic boundary currents. These currents acquire properties (e.g., high nutrient signals) that are communicated to the central Arctic Ocean when they leave the benthos at the shelf break. Details of this shelf-basin exchange are still unclear, but certainly involve eddies and other episodic phenomena. The net result of these disparate halocline water mass processes is a pycnocline that is quite strong in much of the Arctic Ocean, suppressing all but the smallest vertical scales.

The Intermediate and Bottom Layers of the Arctic Ocean

The Arctic Ocean's intermediate or AW layer (300–1700 m) is relatively warm and salty, influenced strongly by inflow from the North Atlantic Ocean. Circulation of this AW layer is tightly constrained by bathymetry, which follows from conservation of angular momentum in the special Arctic case of a nearly constant Coriolis parameter. However, this is not the whole story, because in fact AW fills the entire lower layer of the Arctic Ocean. The spreading of this water laterally across isobaths is still not well understood, although it is thought that small-scale double diffusive mixing plays an important role. The signature of this mixing has been used to diagnose AW age and circulation. AW exits the Arctic Ocean cooler than it entered by several degrees, implying upward heat loss through the pycnocline. Also, weak dynamical forcing of AW within the Arctic Ocean leads to relatively long residence times of several decades. However, recent work indicates that pulses of anomalously warm AW have been and may continue to flow around the Arctic Ocean, forced by climate changes within the Nordic Seas or perhaps even further south. The bottom waters below 1700 m are relatively homogeneous, although they display subtle spatial variability that may indicate renewal by dense shelf waters, geothermal mixing, and boundary currents. In fact, relatively little attention has been given to this part of the Arctic Ocean.

MODELING CHALLENGES

These many diverse boundary forcings and internal processes ensure that numerical modeling of the Arctic Ocean presents special challenges. The unique momentum and buoyancy forcings from the overlying sea ice cover are particularly important to capture in simulations. One aspect of this cover is that it suppresses internal gravity wave generation, leading to low mixing rates that must be accounted for in order to accurately simulate the large-scale circulation. There is also the challenge of resolving in models narrow inflow/outflow straits of 30–50-km width and unusually shallow and broad continental shelves (50–100-m depth for several hundred kilometers north of the Russian Arctic coast), while devoting a sufficient number of grid points to represent the deep (4 km or more) basins and large-scale circulation. Finally, high stratification and a large Coriolis parameter together lead to the smallest geostrophic length scales (~ 10 km or less) in the global ocean, which sets the scale for eddies, fronts, jets, and many other phenomenon in both the real world and in simulations.

WHAT IS REQUIRED FOR PROGRESS

- *Create opportunities for improved understanding of the Arctic Ocean and sea ice as a coupled system, by uniting monitoring and process studies of its individual components.* Unique spatial and temporal scales characterize the sea ice, surface mixed layer, pycnocline, and deep water elements of the Arctic Ocean system, yet these remain poorly quantified and strategies for linking the components need to be better developed. Major steps forward could be made by analyzing seemingly simple concepts and integrative measures like that of the residency time for water masses in these subdomains,

which have yet to be sufficiently established. Studies of the "breakpoint" at which individual elements, such as ice floes, can be considered a contiguous plastic medium or when fracture mechanics can be applied across scales, will define a new way of thinking about the dynamics of these complex entities as unified physical systems.

- *Support work aimed at articulating how dynamics propagate across Arctic Ocean components.* These interconnections occur at a variety of temporal and spatial scales, from the episodic to the long term. Knowledge about how disturbances, such as quasi-periodic atmospheric pressure anomalies like the Arctic and North Atlantic Oscillations amplify or dampen the transport of freshwater plumes and sea ice from the local domain, and interact with ocean eddies and larger forces such as the Coriolis or the movement of North Atlantic waters within the intermediate-depth Arctic Ocean, are fundamentally scaling issues.
- *Catalyze modeling studies that address contrasting space-time scales embodied by a variety of Arctic sea ice and ocean processes.* Simulating multiscale processes that include sharp contrasts of temperature, salinity, inflow/outflows, stratification, fronts/jets, and Coriolis forces constitutes a numerical stability challenge.

2.3. ECOSYSTEMS AND BIOLOGY

2.3.1. Marine Ecosystems

RECOMMENDATIONS

- *Foster baseline studies of key biotic processes, including better quantification of the growth, reproductive, and survival rates of key marine organisms.*
- *Initiate biological and chemical time-series studies, as an important repository of information for understanding the temporal dynamics of marine ecosystems, and assessing the importance of trends, episodic events, and response times to change.*
- *Design optimal Arctic system biological and chemical sampling strategies, with scales matched to the physical and chemical dynamics to which ecosystems are most closely linked.*
- *Unite physical, chemical, and biological simulations at the inherent scales of control on key processes, both under contemporary and future climate scenario conditions.*

SCIENCE CONTEXT

Marine system dynamics across the Arctic are characterized by enormous seasonal and interannual changes in ocean circulation, summer-winter light contrasts, and phase changes of water from liquid to ice, which in turn propagate effects into marine biogeochemistry, productivity, and the shifts in distribution of oceanic life forms, including those of commercial value. In this context, the present and future state of Arctic marine ecosystems is dictated by climate variability and the shadow of climate change.

Climate warming will result in changes to marine biological processes that are complex and interconnected on various temporal and spatial scales. Global climate change simulations for the marine environment predict ocean seawater warming, changes in oceanic stratification, circulation, and convective overturning, as well as changes in sea level and cloud cover, the latter influencing light supply to the surface ocean. These predicted physical changes would directly impact primary production at the base of the food web, which would then likely change the overall marine food web trophic structure in polar regions.

Modeling studies have begun to uncover the potential responses of marine ecosystems to some of these changes. According to one study assessing the sensitivity of six biomes in the world ocean to climate changes, climate warming could substantially reduce the productive phytoplankton zones of the Northern Hemisphere, specifically because of a reduction in the marginal sea ice biome.

Another study focused on the extreme retreats of the sea ice in the Pacific Arctic beginning in 2007 and predicted a strong increase in open-water production of phytoplankton. A recent international workshop on this region concluded that chlorophyll concentrations from satellite views did not follow this prediction, as the recent sea ice retreat does not coincide with a clear shift over time in primary production. This contradiction points out the immaturity of current ecosystem models. The high uncertainty associated with biological process models in combination with the high uncertainties of today's coupled climate models make it difficult to accurately determine ecosystem response to a changing climate.

Other studies focusing on the physics of tipping points and positive feedbacks that could transform the Arctic Ocean into a more or less seasonally ice-free system as the norm raises the notion that Arctic Ocean ecosystems may undergo similarly profound transformations. *Do changes in sea ice harbor a set of one-way, local-scale impacts or do the physical changes create synergies that restructure the entire ecosystem? Or, does the entire ecosystem adapt in some way to these changes?* It is currently unknown how the impact of these disturbances on individual components of the marine ecosystem could be carried up to the scale of the entire pan-Arctic, an outcome that in turn becomes a critical global change question. Thus, a high research priority is to identify and prioritize the key temporal and spatial scales pertinent to biological response related to sea ice reduction. This is a necessary precursor to forecasting ecosystem response to climate warming.

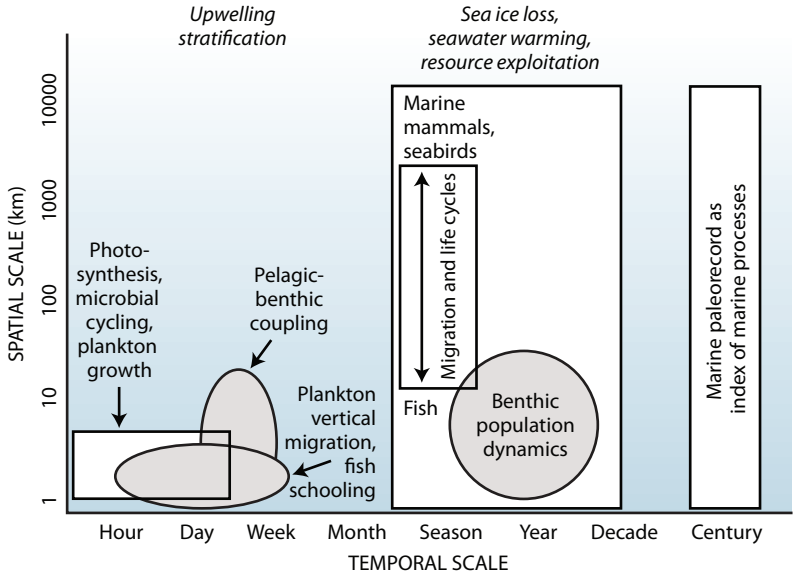


Figure 2.12. Schematic space-time plot of key marine biological processes that influence ecosystem structure, with key physical forcing functions identified in italics.

THE SCALING ISSUE

The marine biological system is complex, with time scales for biological processes ranging from seconds to years and spatial scales ranging from millimeters to thousands of kilometers (**Figure 2.12**). Additionally, one needs to understand the linked physical, chemical, and biological interactions in order to interpret observed biological changes that are occurring and projected as a result of environmental change. The marine carbon cycle is a good example of a biologically essential phenomenon intimately tied to the physical forcings associated directly with global change. Spatial and temporal scales can range from small (meters to kilometers, days to weeks for local-scale productivity), to intermediate (tens to hundreds of kilometers, weeks to months associated with upwelling and stratification), to large (thousands of kilometers, year to decadal in response to long-term losses of sea ice and warming). Within these broad categories, biological scaling issues are complex for marine ecosystems due to varying daily, seasonal, and interannual biological processes. The science thus needs to focus on the combination of scales (small, medium, and large) that will provide key insight into the function of the marine ecosystem if we are to adequately understand, model, and forecast marine biological ecosystem change under a warming climate. Most of the Arctic research on marine ecosystems has been ship-borne observations of organisms and biological processes or satellite-based estimates of chlorophyll. A first step toward scaling, that is, synthesis of the biotic data and associated chemical and physical concentrations and processes affecting open water photosynthesis, has just begun.

One good example of a scaling issue is the heterogeneity of benthic infaunal populations, a key prey base for higher migratory trophic animals such as gray whales, walrus, and spectacled eiders. Although there is uncertainty in

the relationship between rapid sea ice retreat and the interannual primary production in the Pacific marine sector, there are clear changes being observed during the summer period in species ranges for benthic fauna, zooplankton, and fish. Additionally, changes in sea ice conditions have a direct impact at the habitat scale for marine mammals using sea ice as a resting platform. Thus, to understand biological and ecosystem processes, there is a need for benthic sampling from the 3–5-km scale (to study patch dynamics), to the local scale (10–20 km), to the regional scale (100–1000 km), and ultimately to the pan-Arctic scale (10,000 km). This broad range of scales used for sampling will permit scientists to compare and contrast forcings and assess impacts over the entire pan-Arctic domain.

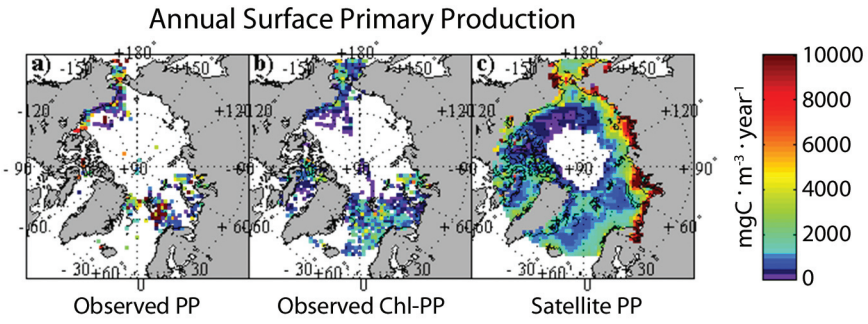


Figure 2.13. Annual observed (a) and predicted (b, c) primary production in surface waters of the Arctic Ocean. (a) Shipboard measures of primary production from many sources. (b) Estimates of primary production that use ship-based measures of chlorophyll to spatially extend estimates of primary production based on a regression of primary production on chlorophyll. (c) Data are estimated from the same regression model and a satellite estimate of surface chlorophyll across the Arctic Ocean. This approach to scaling illustrates the power of incorporating satellite estimates to extrapolate over the domain of the pan-Arctic. The resulting estimates give a rather limited first approximation of the total primary production. The calculations do not include processes, such as algal response to nutrients, nutrient availability, or depth of the mixed layers that are necessary for projecting responses of primary production to environmental changes caused by climate change. *(Unpublished synthesis data from P. Matrai)*

Another example of a scaling issue is the uniformity of net primary production (per unit area) across the five major regions of the Arctic Ocean, 1998–2007. This uniformity is based on observations only, but is this uniformity at this scale of 10,000 km caused by similar physical and chemical processes? There are data on depth of the mixed layer and nutrient chemistry that accompany the primary production measurements from ships. It will be a good test of the scientific understanding of the processes involved if models now under construction are able to reproduce both the similarity and variability in primary production in the data sets. Eventually, satellite data will allow us to monitor whether or not the homogeneity of each region is maintained when marine environments change, and therefore may used to scale productivity measurements to the pan-Arctic level. Satellite data on the spatial distribution of chlorophyll concentrations over the Arctic Ocean could be incorporated into the models (**Figure 2.13**) to reach the goal of achieving a pan-Arctic projection of planktonic primary productivity.

The Unique Role of Sea Ice

The time-space plot developed in **Figure 2.12** identifies many biological marine processes that are important to Arctic marine ecosystems, along with potential perturbations. Sea ice loss, discussed **Section 2.2.4** as a key multiscale physical change in the Arctic Ocean, also controls the very nature of food and energy pathways through the Arctic marine ecosystem. Both lower and higher trophic levels in Arctic ecosystems are closely keyed to the timing of the expansion and retreat of seasonal sea ice and thus the inherent scales of sea ice processes (**Figure 2.10**). Arctic ecosystems are anchored by ice algae or by early stabilization of the water column by melting sea ice. On shallow northern Arctic shelves, the retreating spring ice and cold water temperatures result in a shift of energy to the benthos. In comparison, in more sub-Arctic seas in regions or years with little or no Arctic sea ice, primary productivity is delayed until solar heating provides thermal stratification. In these latter systems, zooplankton are better matched in time to primary production and thus the energy pathways emphasized in the pelagic zone. A shift toward a more open-water-dominated food system could mimic processes at lower latitudes and shift the scales at which the current ice-dominated system operates.

Detailed studies of sardine larvae at lower latitudes illustrate the importance of identifying the most important scale to measure. In this example, broad-scale processes (hundreds of kilometers; e.g., water column stability, phytoplankton and zooplankton stocks) had a significant impact on sardine larval abundance, whereas processes at

the medium scale (10 km; e.g., community level) and small scales (meters; e.g., sardine larval feeding condition, growth rates) were not significantly related. In contrast, benthic-dominated food webs of the Arctic Ocean show great heterogeneity of infauna and should be studied at a range of scales (3–20 km) specifically identified as important to key predators of interest, the large mammals and seabirds. This identification of the important scales to study and model would constitute a testable hypothesis on the evolving scales of key ecosystem change processes.

For marine mammals, there are different adaptation strategies in response to sea ice dynamics and its potential change. Ice-obligate species, such as ringed seal, walrus, and polar bears, require a sea ice habitat for survival. Ice-associated species, such as ribbon seal, use ice for molting and weaning pups, but after the short springtime spend their time foraging over long sub-Arctic distances. Seasonally migrating species take advantage of the high summer productivity and generally arrive after the sea ice has retreated northward. Thus, sea ice is critical over a wide variety of temporal and spatial scales for organisms that migrate thousand of kilometers for food and reproduction.

MODELING CHALLENGES

Key to gaining a pan-Arctic understanding of marine ecosystems will be robust ecosystem models that incorporate the major trophic components and physical forcing parameters across a range of temporal and spatial scales (**Figure 2.12**). Successful models must be anchored by field data to evaluate forecasting skill in depicting changes in the regional and pan-Arctic marine ecosystem; short-term responses to environmental variability, seasonal to years, can be used in this context. For pelagic ecosystems, community production models are needed to translate concentrations of nutrients before and after spring and summer into net production of plankton. Food web models of the plankton will allow predictions of the impact of lengthening of the period of open water on zooplankton and fish, including commercial species. For benthic food webs and fishery questions, population dynamic models coupled with bioenergetics models, sea ice distribution models, and prey distribution models—all with the characteristic scales discussed above—is needed to move the science forward. This composite modeling program would allow a detailed investigation of how key organisms and ecological processes would respond to climate changes as well as anthropogenic forcing, such as catch pressures, as new fishing grounds are opened. A key aspect would be to develop realistic trajectories and identify thresholds of climatically driven ecological change.

Although work has been ongoing, there remain significant challenges. Issues include identification of the most critical biological processes that must be measured through field process studies and measurement campaigns, and in particular, how to scale point and patch measurements up to the larger marine ecosystem domain.

WHAT IS REQUIRED FOR PROGRESS

- *Foster baseline studies of key biotic processes, including better quantification of the growth, reproductive, and survival rates of key marine organisms.* Such small-scale measurements are needed to adequately scale up to population size estimates (medium scale) and regional and pan-Arctic ecosystem models (large scale), under ambient as well as climate-modified physical changes anticipated for the future. A digital encyclopedia of such information would constitute an important data resource for Arctic marine ecosystem modelers for both model calibration and validation.
- *Initiate biological and chemical time-series studies, as an important repository of information for understanding the temporal dynamics of marine ecosystems, and assessing the importance of trends, episodic events, and response times to change.* This precursor is necessary for developing procedures to scale up to the temporal domains necessary to analyze regional and pan-Arctic ecosystem dynamics. Multivariable time series can be analyzed using statistical techniques to uncover potential links that can then be tested in deterministic models. The sensitivity of Arctic marine ecosystems to imposed change, and their capacity to adaptively reconfigure themselves and/or to remain resilient are today critical unknowns.
- *Design optimal Arctic system biological and chemical sampling strategies, with scales matched to the physical and chemical dynamics to which ecosystems are most closely linked.* The tight coupling of physical and biogeochemical processes imparts control over the

biological features of marine ecosystems, which vary from the environment of the individual up to whole communities and populations of important marine organisms. Nutrient concentration data collected in the late winter and early spring would fill a major gap in understanding the chemical dynamics in the plankton.

- *Unite physical, chemical, and biological simulations at the inherent scales of control on key processes, both under contemporary and future climate scenario conditions.* Anticipated patterns of high-latitude changes to marine ecosystems can cascade and potentially become amplified through nonlinear responses and thresholds. Concerns regarding irreversible system states and positive feedbacks, thus far articulated most cogently for the sea ice loss question, are also relevant in terms of reconfigured Arctic ocean ecosystems.

2.3.2. Terrestrial Ecosystems Including Freshwater

RECOMMENDATIONS

- *Develop research programs to advance understanding of mechanistic controls on processes operating over contrasting spatial and temporal scales.*
- *Create observational networks that can support multi-scale analysis of the space and time characteristics of key terrestrial and aquatic ecosystem processes.*
- *Foster research that focuses on representing fine-scale processes in models that are used as tools to address questions at coarser scales, including those appropriate to the domain of the pan-Arctic.*

SCIENCE CONTEXT

Arctic terrestrial and freshwater ecosystems provide many direct and indirect benefits to society. These benefits, generally referred to as ecosystem services, are derived from ecosystem processes, which provide food, fuel, and fiber; regulate floods, disease, and climate; and support aesthetic values, spiritual traditions, recreation, and education. To ensure the long-term sustainability of these services, through proper stewardship of the ecosystems that convey these services, requires a multiscale understanding of the Arctic—from the scale of small Arctic terrains that span hillslopes and small domains (where human management is focused) to whole regions—a capability that is not currently available.

In addition, terrestrial ecosystems play a central role in climate regulation, in terms of both vegetation character and soil carbon storage and their links to water, energy, carbon dioxide, and trace gas (e.g., methane and nitrous oxide) exchange with the overlying atmosphere. Vegetation distribution is a sensitive indicator of climate change. The paleo record, for example, shows enormous northward shifts of boreal forests during warm periods within the last 10,000 years. Vegetation changes alter the character of the Arctic land mass' thermal signature, including its reflectivity (reduced with more green biomass, increasing solar radiation absorption), ability to capture windblown snow (creating an important water resource for the plants during snowmelt), and capacity to dry soils (as evapotranspiration increases with more vegetative biomass). Arctic ecosystem soils are a globally important repository of land-based carbon and there are great concerns about how a warmer growing season, degrading permafrost, and exposing soil to oxidizing conditions will regulate their collective contribution to global CO_2 gas fluxes. Further, these systems are increasingly becoming vulnerable to drying as well as insect infestations with resultant changes in fire frequency and severity, once again bearing impacts on carbon balance but also on residents of the North. Many of the statements made above were derived from site-specific, and indeed plot-specific, experiments, yet the implications are borne out over a much broader spatial domain, including the full pan-Arctic.

THE SCALING ISSUE

Understanding ecosystem structure and function is largely derived from a tradition based on measurements taken over a spatial scale of but a few square meters and over temporal scales of minutes to a few years. To address today's pressing issues of Arctic environmental and climate-related change, it is essential to translate fine-scale knowledge to larger regions and to longer time periods.

There have been rapid advances in global satellite surveillance systems, geospatial models and data sets, airborne atmospheric monitoring, and flux towers—among many other technologies—capable of depicting the state of

ecosystems over spatially large extents and at a relatively coarse grain. These developments represent a formidable information resource but at the same time a substantial technical challenge rests in harmonizing results obtained from fine-scale studies into this larger context.

Ecosystem processes have traditionally been depicted at well-defined spatial and temporal scales (**Figure 2.14**). Some processes have been addressed at a relatively fine scale (e.g., leaf photosynthesis), while other processes have been depicted, by their very nature, at a regional scale (e.g., wildfires). The controls on photosynthesis, decomposition, and nutrient cycling in the Arctic have all been measured and modeled at the scale of individual tussocks, stream riffles, and small patches of lake sediments.

One approach to assessing responses at the pan-Arctic scale would be to model these processes for every plot (approximately the meter-squared scale) across the extent of terrestrial ecosystems in the Arctic. However, the computational burden and limits in knowledge on how to explicitly parameterize models that depict these processes at this scale is clearly prohibitive for even an average-sized watershed (hillslope and catchment scales in the figure), and requires the development of strategies for projecting how fine-scale processes are manifested at coarser scales.

In fact, there has been progress in representing at coarser scales the operation of some fine-scale ecosystem processes relevant to the climate system (**Box 2.3**), for example, primary productivity in Arctic land ecosystems. In the early 1990s, regional carbon cycle models only considered fine-scale ecosystem processes such as photosynthesis and decomposition in estimating carbon exchange. More recently, these models are considering the dynamics of fire at regional scales and are now better able to partition effects of climate change and disturbance on simulated changes in carbon storage at the regional scale. Although research to date has illustrated how to scale some component processes, the challenge that now faces the scientific community is in scaling all the *relevant* fine-scale processes to coarser scales. Specifically, the challenge lies in identifying and then representing those processes that propagate to the scale of the whole Arctic in models that operate across the full domain of the Arctic system.

Observational systems employing both fine- and coarse-scale measurements are required for evaluating whether scaling approaches have worked. For example, carbon flux studies can use technologies that employ chambers (relevant to one square meter), short towers (relevant to one hectare), and tall towers (relevant to hundreds of square kilometers). The mechanistic understanding of carbon exchange is generally provided by the chambers, but this information needs to be scaled up to the region to determine why the region is losing or sequestering carbon. Remote sensing is an important tool for scaling fine-scale measurements to the regional scale, particularly when observations at the regional scale can be used to evaluate the scaling application. Measurements at the tall-tower scale provide the regional data to evaluate whether scaling to the region has worked. Analogous to the spatial considerations of scaling, long-term observations are needed

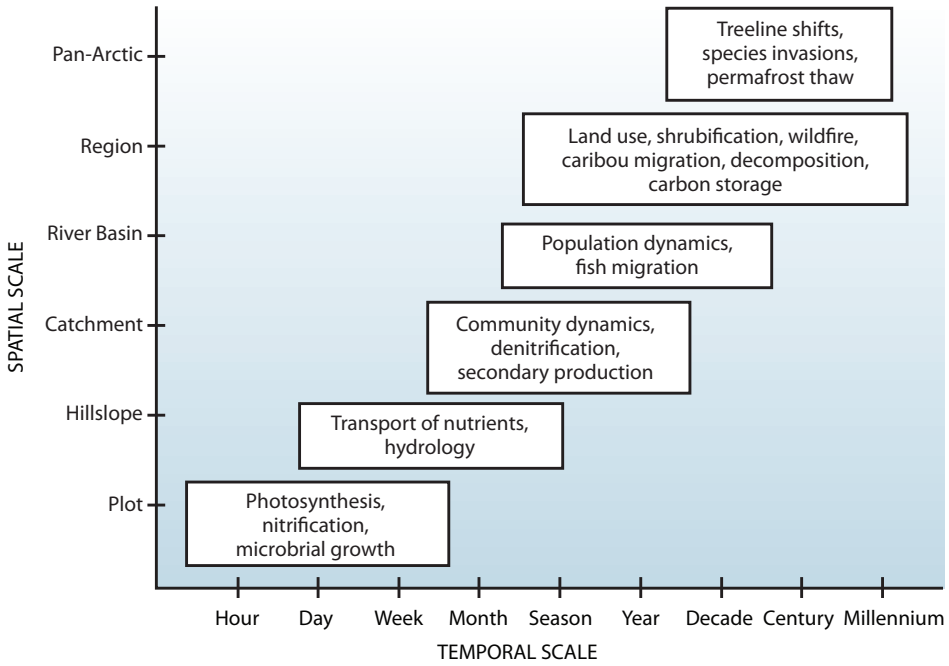
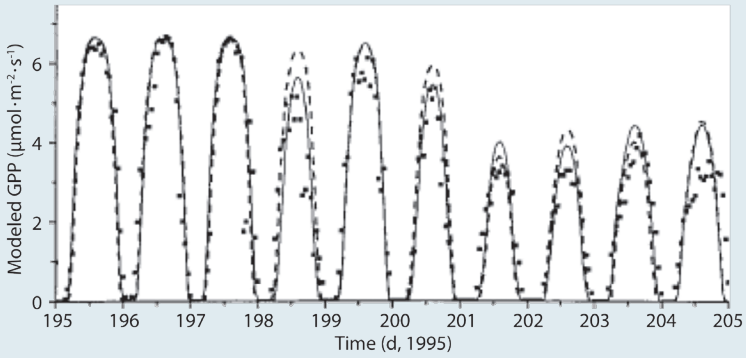


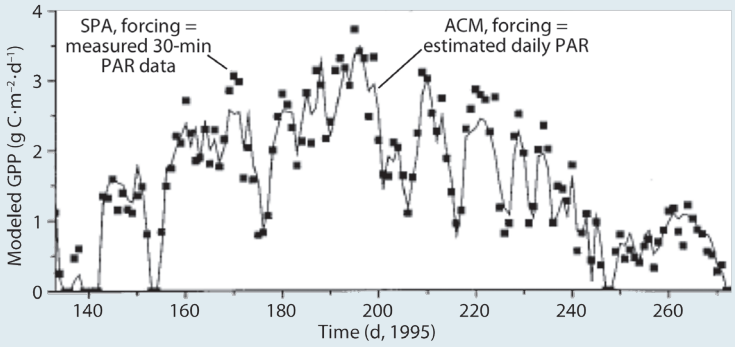
Figure 2.14. Dominant processes operating at different temporal and spatial scales in terrestrial ecosystems of the Arctic.

BOX 2.3. SCALING OF AN ECOSYSTEM PROCESS

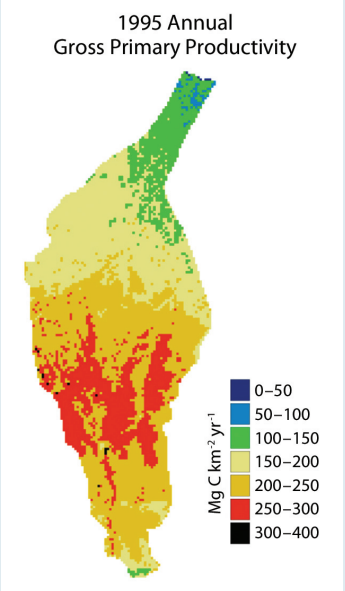
Site-specific information is important to developing an understanding of key biogeophysical properties of Arctic watersheds. However, to gain broader relevance and to explore the implications of these properties at the regional scale, scaling strategies are critical. For example, a group of scientists used gross primary production (GPP) measurements on plots in the Kuparuk River Basin, Alaska, along with meteorological data, to develop a scaling protocol to enable hourly gas exchange data to be used for daily estimates of GPP. **Box Figure 1** shows hourly GPP predictions using measured photosynthetically active radiation (PAR) and a detailed, ten-canopy layer, half-hourly time step model (Soil-Plant-Atmosphere [SPA]). In **Box Figure 2**, SPA predictions of GPP have been scaled to develop a simpler model (Aggregated Canopy Model [ACM]) that applies to whole canopies on a daily time step. This simpler model required many fewer and more readily available parameters and input data. The authors also estimated the GPP for the entire 9200 km^2 river basin (**Box Figure 3**) through the use of the simple ACM model of daily GPP and vegetation and meteorological constraints on production of individual square kilometers derived from field surveys, distributed climate stations, a land cover data base, and satellite data (NDVI). The river basin estimate is a projection based on scaling protocols, which moves understanding from hourly to daily estimates (see also the Primer on Scaling in **Appendix 1**).



Box Figure 1. Predictions of hourly GPP using measured hourly PAR data (squares). *(From Williams et al., 2001, copyright by the Ecological Society of America)*



Box Figure 2. The simple ACM model predicts daily GPP forced with measured 30-min PAR (lines). It compares well with the more complex SPA model (squares). *(From Williams et al., 2001, copyright by the Ecological Society of America)*



Box Figure 3. Predicted gross primary production in the Kuparak River basin, AK, from the sum of individual days in 1995. The resolution is 1 km^2 and the units are 10^6 g C km^{-2} yr^{-1}. *(From Williams et al., 2001, copyright by the Ecological Society of America).*

to evaluate whether the scaling of short-term observations to longer time scales works.

Scaling not only requires representation of fine-scale processes at a coarser scale, but also the representation of interactions that are taking place at these coarser scales. For example, caribou grazing might not be a critical consideration when modeling plant production at the plot scale. However, when modeling production at a catchment or river-basin scale, caribou grazing could be vitally important. Herbivory can also influence the pattern of vegetation changes at the river-basin scale. For example, moose prefer willows over alders on newly vegetated floodplain silt bars along rivers in Alaska. Thus, preferred herbivory on willow accelerates the transition of floodplain willow sites to alder sites. Because alder is a nitrogen fixer, the transition to alder is important for the nitrogen economy as alder sites transition into forest sites. The regional scale brings in other process such as the seasonal migration of caribou, land use, and fire. Finally, large changes in treeline and permafrost integrity may influence ecosystem function and structure over the pan-Arctic at century to millennial time scales.

The decadal scale is particularly critical for policy decisions, and scaling up to decadal scales with models is a major challenge because appropriate data at decadal scales are often lacking. While the enhancement of observational systems to make continuous measurements over decadal to century time scales holds promise for providing these data, the scientific community cannot wait for decades to conduct this scaling. Manipulative experiments represent a great resource for testing decadal-scale model behavior than are generally captured by shorter duration studies. Also, links to paleo studies to test models of vegetation dynamics holds promise for evaluating decadal to millennial-scale behaviors of models.

An important issue with respect to temporal scaling concerns the use observational time-series data to constrain the behavior of models at various temporal scales. Data assimilation is an important technique that uses time series data to optimize parameters in a process model. As parameters in a process model are associated with dynamics that operate at different time scales, for example, fast photosynthesis responses or slow decomposition processes, the assimilation of data to constrain parameters is a powerful means to combine information, across a range of time scales, in a modeling analysis. Data assimilation techniques have great utility for temporal scaling as continuous long-term time-series data are collected by observational systems in the Arctic (e.g., AON, SAON).

WHAT IS REQUIRED FOR PROGRESS

- *Develop research programs to advance understanding of mechanistic controls on processes operating over contrasting spatial and temporal scales.* Research to develop coarse-scale models must build upon the mechanistic understanding gained from studies conducted at fine scales. Ecosystems represent highly linked physical, chemical, and biotic domains through which process dynamics reverberate. A search for the key scales and conditions under which component processes are amplified or dampened and signals carried through each of the three domains will constitute a key step forward.
- *Create observational networks that can support multi-scale analysis of the space and time characteristics of key terrestrial and aquatic ecosystem processes.* Information gathered from a new generation of large-scale and long-term observation networks, linked to smaller-scale and long-term observatories (e.g., NSF Long-Term Ecological Research sites) should yield new insights into the coherency of ecosystem response to climate and other forcings across scales.
- *Foster research that focuses on representing fine-scale processes in models that are used as tools to address questions at coarser scales including those appropriate to the domain of the pan-Arctic.* Although the goal is to improve predictive capabilities using models that provide coherent results across a spectrum of temporal and spatial scales, such models will be difficult if not impossible to construct without process-level studies and analysis of observational records. Models must be part of a unified experimental and observational networking strategy.

2.4. HUMAN SYSTEMS

2.4.1. Arctic Communities

RECOMMENDATIONS

- *Replicate case studies and surveys to generate cross-site comparisons, essential for securing large-scale understanding.*
- *Systematically improve completeness, access to, and integration of human-dimensions data with biogeophysical information.*
- *Provide Arctic residents and crisis managers environmental information at local scales and closer to real time.*

SCIENCE CONTEXT

Although uncertainty has always been a part of life in the North, unprecedented and decidedly nonlinear changes to high-latitude ecosystems are confounding livelihoods in both urban and rural settings. Changing climate and weather patterns, with related changes in fire and hydrological regimes, interact in complex ways with industrial and resource development, socioeconomic changes, as well as internal and external geopolitical conflicts. Some biophysical system changes are sudden and catastrophic, for example, storm-, wind-, and wave-driven coastal and river erosion. Others are much slower, and cumulative, in their onset and impact. In addition, colonial, cultural, and historical legacies each influence livelihoods today. Climate, social, and ecological models for these changes therefore abound, accompanied by stark uncertainties regarding how they will affect human activities at household, community, and institutional policy/regulatory scales.

Climate change is prompting new research into human vulnerabilities and risk. Although recent scholarship has provided a variety of standardized Integrated Assessment (IA) frameworks for facilitating local-scale assessment, they remain limited by their case-study approach, which tells us little about spatial- and temporal-scale interactions. In addition, there has been almost no formal collaboration between Arctic researchers and researchers working elsewhere in the world to explore the benefits of cross-border and cross-regional synthesis. The intent here is to advance a general and comparative framework for understanding, for facilitating a better collaborative environment, and for working through genuine stakeholder input to design more effective and culturally appropriate assessments that link science to policy, that in turn will help design adaptive responses to ongoing Arctic change.

THE SCALING ISSUE

Individual people comprise the atomic units for most research on Arctic communities. People gather into larger units of many overlapping and loosely defined kinds such as households, families, social groups, and organizations. Any of these larger-scale units could be important for understanding a particular community, and how it compares with other places. Well-developed social-science methods exist for study of various units, although the same methods do not necessarily work well across different scales.

Who is vulnerable, and to what? Who is resilient, and to what? Our ability to evaluate the wellbeing, vulnerability, and resilience of communities and the ecosystems they rely on, and implement policy and regulations that address these needs, depends largely upon our ability to translate what we already know about "large-scale" drivers of change to scales that matter to people and livelihoods. In this context, day-to-day weather, precipitation trends, shifts in seasonality, and wildlife phenology matter greatly. In addition, there is a significant challenge in matching policy implementation, traditionally carried out using its own set of spatial and temporal scales, with both large-scale changes and small-scale needs (**Box 2.4**). No single conceptual, theoretical, or modeling framework has emerged that is capable of distilling the interactions of large-scale drivers into high-quality, locally relevant information.

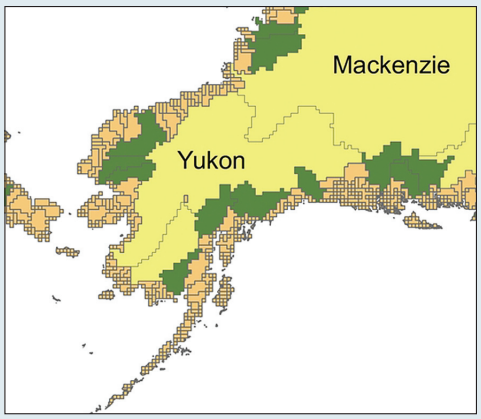
An Example of Scale Approaches in Arctic Demographic Research

Demography, or the study of population, focuses on some of the most fundamental and best-measured social dynamics. Analytical steps, from individuals to communities, regions, and states, are comparatively straightforward in demographic data, providing a best-case path for exploring some key issues associated with scaling in social research. For example, the population of one community is basically the

BOX 2.4. HUMAN DIMENSIONS RESEARCH: SCALING COMPLEXITIES BORN OF OTHER DISCIPLINES

Residents of the Arctic live in a complex milieu of social and also biogeophysical conditions, all highly dynamic and arguably more extreme than what is typically encountered at the lower latitudes. How might human-dimensions data such those plotted in **Figures 2.15–2.17** be integrated with climate or other physical science data, on an Arctic-system (as opposed to local-community) scale? Social and economic data in general describe socially defined units such as town, borough, or state, and the typical points of entry into the social sciences are multiple, as indicated by the tables in this box (right). In contrast, natural sciences data are displayed using different kinds of spatial units such as watersheds or grid cells. One approach to data integration is to map the social units in terms of grid cells, ready for combination with geospatial Earth system science data. The box figure (below) shows an example involving 23 administrative subdivisions of Alaska, depicted as collections of the 25 km^2 equal-area grid cells. Combining these with watershed delineations, among many other possibilities such as biomes or climate regimes, allow important re-samplings of the social science data sets to be made with biogeophysical information. These combinations permit new issues of consequence to the inhabitants to be addressed. In this case, we could ask questions such as: *What are the distributions of landscapes above and below particular administrative units, how are they changing, and how do they regulate rural water supply? How much rain or snowmelt is available as a water resource at particular times of the year and how is its variability changing in response to climate change? Should coping strategies for Arctic communities best be applied at local or administrative or watershed-specific scales?* The classification systems depicted in this box are both valid. Combining different accounting systems highlights the need for a common nomenclature; that is, if system-level understanding is the ultimate goal of the community, standardization is required.

Box Figure 1. Administrative subdivisions of pan-Arctic Alaska, mapped in terms of EASE grid cells. Dillingham Census Area at lower left.



Box Figure 2. Drainage basin boundaries in Alaska, highlighting the organization of the landscape from an important biogeophysical perspective, namely drainage of the landmass. The map highlights many scales of interest, from the largest Yukon River basin down to the many small coastal watersheds of the region and the disparity with the human administrative divisions across the same region. Many biogeophysical data sets are already gridded and frameworks for their use are well-established-uniting these with human dimensions data sets as in Box Figure 1 will enable new lines of inquiry to be pursued.

SCALES OF POLICY & REGULATION

Temporal
- Historical orthodoxy (26 Game Management Units, or GMUs, were established in 1956; few subdivisions and no reconfigurations made since)
- Decisions must be made years to months in advance
- Legislative cycles
- Emergency orders

Spatial
- Institutional and political borders (e.g., nations and sub-national units, communities, individuals GMUs, state and federal protected lands)

SCALES OF HOUSEHOLD EXPERIENCE

Temporal
- Season
- Animal life history (e.g., rut, migration)
- Wage season (e.g., fire jumping)
- Daily, weekly (can adjust tactics to weather and environmental cues)

Spatial
- Working landscape, "foodshed" (e.g., known places, culturally important harvest areas)

SCALES OF ECOLOGICAL CHANGE

Temporal
- Succession (fire regime, invasive species, successional change)
- Seasonality (breakup, freezeup, growing season)
- Animal life history (e.g., rut, migration)

Spatial
- Landscape, topography
- Watershed

sum of individuals living there. Population changes over time with the number of births and deaths (their difference being "natural increase") plus the number of in-migrants and out-migrants (their difference being "net migration"). **Figure 2.15** gives a time series of population changes from 1990–2006 in the southwestern Alaska fishing town of Dillingham. During the first decade of this period, the town grew by 20%, but after 2000, population leveled off and then declined slightly. Births substantially exceeded deaths throughout the whole period, as shown by light and dark bars in the lower part of the figure—so natural increase steadily favored growth. Net out-migration since 2000 caused the leveling and then decline of total population.

Figure 2.15 takes information about a few thousand people and scales it up to the level of the community they form. Thus, at the community level, we see a pattern of change partly driven by demographic, socioeconomic, and health conditions affecting birth and death rates, but also partly by changing conditions in the fishery that provides livelihoods.

A further step up in scale allows comparisons across communities. **Figure 2.16** presents similar plots of population changes in four other predominantly Alaska Native (Yupik) communities that are also within the Dillingham Census Area. Like Dillingham itself, each place experienced periods of growth, stability, and decline. Some of the place-to-place variations could be random, but they also challenge researchers to identify systematic causes—*Why did the population of New Stuyahok and Togiak, for example, grow steadily through the first decade of this period, much like Dillingham, but then level off and decline?* The other two villages in **Figure 2.16** each followed a somewhat different pattern, in which net migration played a more dominant role. Such fluctuations reflect interactions between external forces and the qualities or internal dynamics of different communities. Studying them can provide important clues on what to expect as conditions change elsewhere in the future. The highly varied sensitivity of individuals and communities to external forces remains a key issue in Arctic social science research.

Figure 2.17 steps back further (i.e., *upscales*), combining all Dillingham Census Area communities in one plot at center left. At this scale, we can compare a number of other areas such as the North Slope Borough or Northwest

Arctic Borough. Some areas exhibit patterns of steady growth, while others show recent declines. **Figure 2.17** lacks the details of **Figures 2.15 and 2.16**. Community-level time plots are based on much smaller numbers, and consequently show erratic year-to-year variations that obscure underlying trends. Confidence bands at local scales would be wide, encompassing the possibility of increasing, declining or stable population. Many other social and health indicators share this property of being highly variable at small scales and over small numbers of individuals. **Figure 2.17** brings a new possibility that becomes increasingly valuable as scale increases: a quantitative model of change. In this case, a multilevel quadratic model can be used to roughly summarize population changes that overlay or combine large-scale with local-scale trends. As human-dimensions research moves from local case studies to larger-scale comparative analysis, formal models become increasingly useful and commonplace.

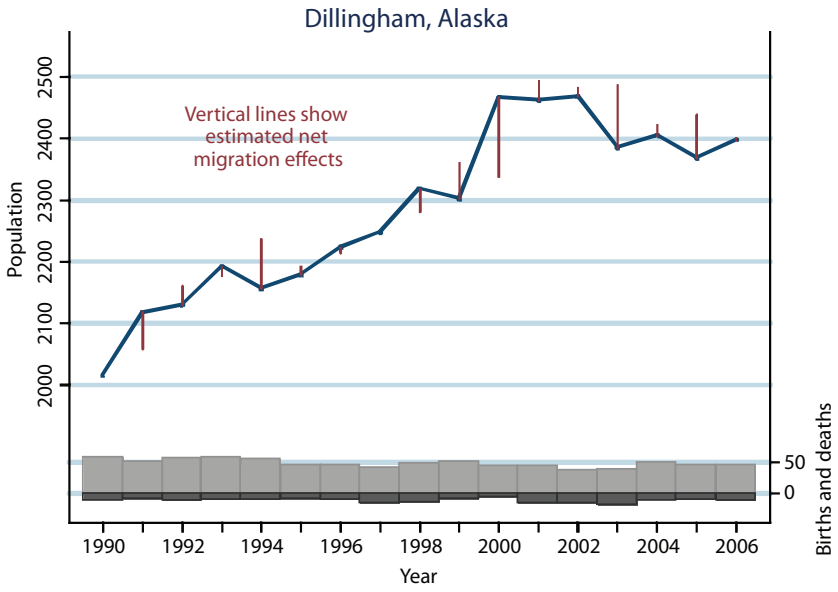


Figure 2.15. Components of population change in the town of Dillingham, Alaska, 1990–2006.

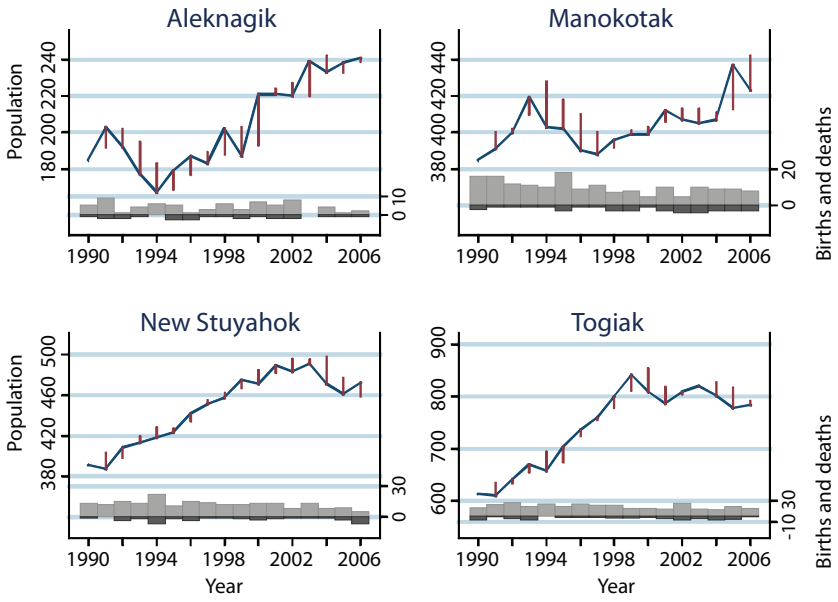


Figure 2.16. Components of population change in four Dillingham Census Area villages, 1990–2006.

Our discussion thus far concerned mainly issues of spatial scaling, as they are applied to human geography. In principle, thousands of indicator variables (e.g., any information recorded for U.S. counties) could be added to the pan-Arctic spatial framework described in **Box 2.4**. From a practical standpoint, time series can be difficult to obtain for social scales smaller than sub-national. Nevertheless, it is still important to briefly mention the key temporal scaling issues for those data sets that are today being collected or anticipated to be collected. Information at community and larger scales commonly is recorded by year, which often makes a convenient metric for integration. But for some purposes, such as oil-spill response, the relevant time scales are much shorter, on the order of hours to days rather than years (although long-term consequences might become visible over years or even decades). Political cycles of two to four years affect many policy decisions, so that consequences that might unfold more slowly sometimes get lower weight. Uniting these different time perspectives requires additional new research.

Human Dimension Data Requirements and Challenges

Basic demographic, economic, and health statistics are commonly collected by governmental agencies, which have access to resources that dwarf those of

most research projects. Researchers often benefit from such data, but information does not necessarily exist (or it is not openly accessible) across the range of scales—from specific communities to regional or pan-Arctic—needed by researchers. Social science data often also lack continuity over time, making it difficult to track change. Moreover, the particular variables needed to address research questions may never be collected. Dedicated surveys and case studies can supplement basic population data, but these tend to be scale-specific, dealing with a few selected communities or, conversely, region-wide with little geographic resolution.

Research aimed at meeting the needs of the environmental policy and management communities confronts a number of significant, scale-related challenges. Given the complex causalities of social systems, scientists need substantial volumes of data to detect and understand signals amidst much noise. Geographically specific time series of health and social indicators, and replicated case studies or surveys of northern residents are currently rare, but much needed for practical research. Without geographical specificity and time series, it is difficult to secure indicator data at the community scales, or precisely where it is most needed. Conversely, without replication, it will be difficult to establish the generality and utility of research results for better management, because conclusions will be based on stand-alone case studies or surveys.

Local-scale and real-time information become particularly critical with respect to fast-moving phenomena such as oil spills or extreme weather. Impacts of climate shifts will also have costs, at local levels and over shorter time scales, as they affect particular resources, transportation, infrastructure, and activities (see **Section 4.4**).

New data compendia should be developed through: targeted surveys; enhanced monitoring, recording, and publication of indicators by government agencies; and more sharing of existing records (such as logs of transportation or other weather-dependent activities) maintained by the private sector (e.g., energy companies). Alongside a broader effort at producing and releasing data, starting at community-level or smaller scales, we need significantly more work on integration strategies. The place/year integration approach shown by examples in this section is one possible route, but both this approach and others need

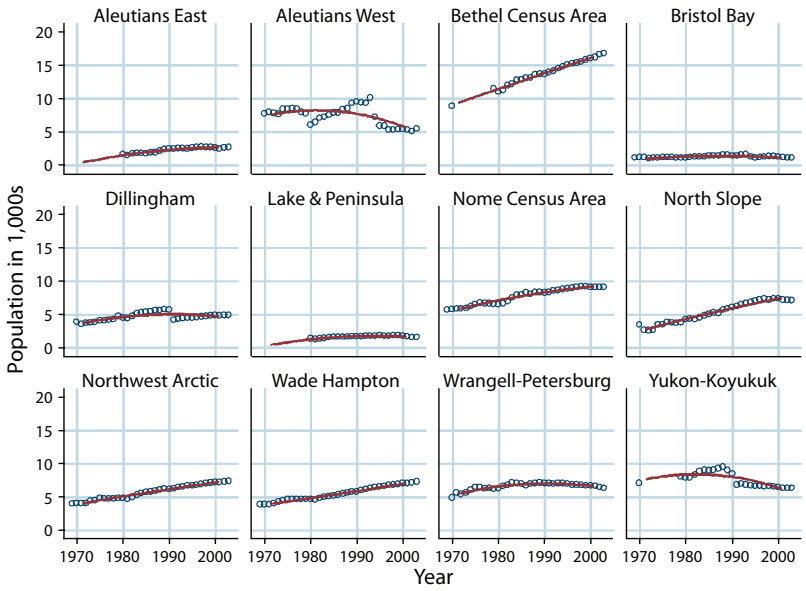


Figure 2.17. Observed and modeled population trends in 12 Alaska administrative subdivisions, 1970–2003. Dillingham Census Area at center left.

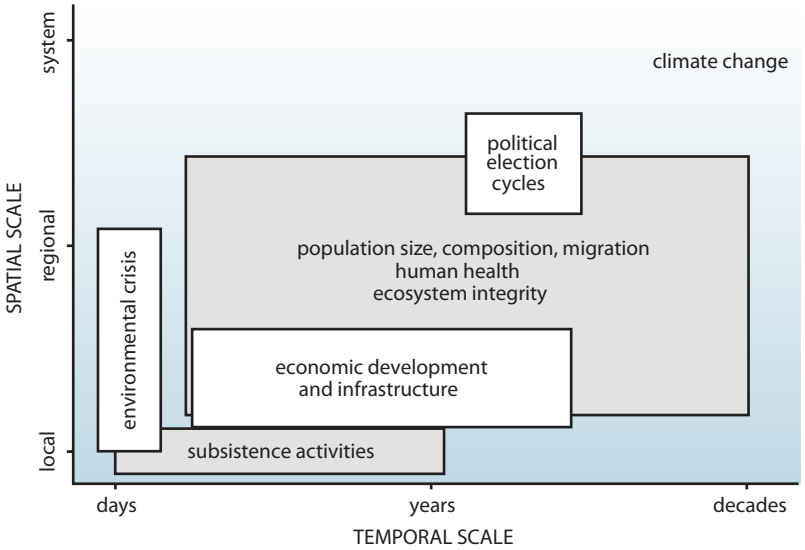


Figure 2.18. Schematic representation of some overlapping temporal and spatial scales involving human communities in the Arctic.

development. Modeling and other analytical methods that work with such integrated data sets are still in their early stages of development.

WHAT IS REQUIRED FOR PROGRESS

- *Replicate case studies and surveys to generate cross-site comparisons, essential for securing large-scale understanding.* Although data collected by the government is a mainstay of social science research, information gathered by scientists to support question-driven research is also an essential knowledge commodity. In this context, the value of local-scale information collected in the best traditions of human dimensions research, will find new value in addressing new global-change-driven issues, like Arctic climate change. A sufficient number of case studies will be required for comparative studies to position a particular site within the context of larger pan-Arctic patterns, and indeed to identify such patterns.
- *Systematically improve completeness, access to, and integration of human-dimensions data with biogeophysical information.* New approaches in social research are needed to improve and fully utilize the limited data resources. Multivariable statistical methods (e.g., regression-type modeling, including time series and multilevel analysis) could aid research particularly as we move up to larger scales in the pan-Arctic system. A focus on the Arctic climate change question, which is of sufficient interdisciplinary breadth, could help catalyze the wider application of statistical and other modeling approaches, along with the development of new synthesis techniques.
- *Provide Arctic residents and crisis managers environmental information at local scales and closer to real time.* Climate change, while inherently long term and pan-Arctic in nature is a part of a larger environmental change issue, which also has shorter temporal and spatial scales. Chief among these are the influence of natural events, such as storms and coastal erosion, and human-made events, such as oil spills. The social science data and analytical methods needed to provide warning, assessment of damage, and response are in their infancy but ripe for new development.

3. THE ROLE OF SCALING IN INTERDISCIPLINARY ARCTIC AND EARTH SYSTEM SCIENCE

3.1. INTRODUCTION

It is no longer news that the Arctic is changing—broad-scale increases in air temperature, rapid gains/losses in lake area, major "greening" and geographic shifts in vegetation, historic reduction in seasonal sea ice, glacier melt, permafrost thaw, increased river flows, longer ice-free periods, and diminished snow cover. Changes are in many cases coordinated and systematic, and some observed rates of change are substantially faster than state-of-the-art models today can predict. A grand challenge thus faces the scientific community—and indeed society at large—to interpret, understand, forecast, and respond to reverberations of Arctic system change to other parts of the Earth system. Answering this call will require a strategy to integrate emerging knowledge of complex Arctic-centered dynamics with assessments of the larger Earth system. Because of the highly coupled character of human and biogeophysical systems in the Arctic, a major step forward will be to develop an improved understanding of how the critical linkages are "wired" together and how individual disciplinary notions of scale can be unified.

The Arctic research community has substantial experience in synthesizing complex interdisciplinary perspectives. We seek now to address the urgent challenge of understanding how Arctic system dynamics are teleconnected to and affect other parts of the globe. This report presents a brief discussion of interdisciplinary scaling challenges across two strategic domains: Arctic-centered tipping points and the role of Arctic terrestrial ecosystems in the broader Earth system. Each example still requires substantial improvement in our understanding and in reducing uncertainties about how Arctic change affects the twenty-first century Earth system. In both cases, the focus is on climate change, as an overriding backdrop of Arctic system change and as one of its principal forcings.

3.2. TIPPING POINTS IN THE ARCTIC SYSTEM

RECOMMENDATIONS

- *Support research to identify thresholds.*
- *Better collate and integrate information over key system components and at different scales.*
- *Develop scenarios of the consequences of alternative management options.*
- *Match scientific research to the needs of decision-makers at multiple scales.*

SCIENCE CONTEXT

A threshold, which is also often referred to as a tipping point, is the state beyond which there is an abrupt change in the system quality, property, or phenomenon being considered, or where small changes in one or more external conditions produce large and persistent responses in the system. Thresholds occur when external factors, positive feedbacks, or nonlinear instabilities in a system cause

changes to propagate along potentially irreversible pathways. Once a threshold is crossed, the system in question may be unable to return to its previous state. For example, it has been proposed that the Arctic may be near a threshold between increased solar absorption in the ocean during summer and its ability to regrow first-year sea ice during the following winter.

THE SCALING ISSUE

Although thresholds are fundamentally an issue of temporal scale, the factors that lead to system-wide thresholds may be manifested across a spectrum of temporal and spatial scales. The example of sea ice loss discussed earlier (**Section 2.2.4**) illustrates several issues of temporal and spatial scale. Sea ice loss involves warming of the Arctic, heat transport from the tropics to the Arctic via the atmosphere and ocean, and melt in the Arctic. Thus, understanding processes at multiple temporal and spatial scales—extending beyond the pan-Arctic—is essential to understanding when system thresholds may occur.

Thresholds may occur in physical, ecological, and human components of the Arctic, and may involve feedbacks and impacts in physical, ecological, and human systems, both within and outside the Arctic. For example, although summer sea ice loss can be characterized as a physical process, its link to climate change involves human systems (i.e., the burning of fossil fuels) and ecological systems (the ability of marine and terrestrial biota to take up emissions of carbon dioxide from the burning of fossil fuels). Furthermore, the impacts of the loss of summer sea ice have substantial implications for ecological and human systems. For example, the warmer waters and deeper light penetration of an ice-free summer have the potential to influence ecological systems in the Arctic Ocean and the increased transportation and resource access is almost certain to influence economic and political systems globally. Furthermore, the potential for sudden, unanticipated shifts in system dynamics makes planning, preparation, management, and policy very difficult. These sudden changes to system dynamics are not well understood, but they are extremely important if managers and policymakers are to succeed in developing mitigation and adaptation strategies in a changing world.

If climate change is pushing the Arctic system toward thresholds, what can be done by decision-makers and others to better cope with the threat of transformative change? Although the science of thresholds is still in its infancy, there are actions that, taken together or separately, can improve the understanding of thresholds and increase the likelihood of success in developing management and adaptation strategies in a changing climate, before, during, and after thresholds are crossed. The emphasis should be on research that identifies thresholds and tipping points, better integrates requisite data sets across scales and disciplines, and assesses alternate futures for adaptive management. The broad set of time-space plots shown in **Section 2** of this report is a testament to the challenge ahead, and it will become ever more important for traditional disciplines to develop a shared nomenclature, develop methodologies for cross-component "hand-shakes," and assess the relevancy of particular scales that determine full-system behaviors. These obstacles to progress will require new mathematical and statistical techniques to help handle the many orders of magnitude in scale. This constitutes a difficult numerical stability challenge for modeling and data interpretation.

WHAT IS REQUIRED FOR PROGRESS

- *Support research to identify thresholds.* Better integration of existing monitoring information across a range of spatial scales will be needed to detect potential thresholds, and research will need to focus on systems undergoing a threshold shift to better understand the underlying processes. In a world being altered by climate change, managers and decision-makers may also have to be increasingly nimble, and adjust their goals for desired states of the system away from static, historic benchmarks and focus on increased resilience and adaptive capacity as measures of success. Reliable identification of thresholds in the Arctic system across different subsystems should be a priority given their potential to reverberate throughout the system.
- *Better collate and integrate information over key system components and at different scales.* Once the key factors controlling adaptive capacity and resilience of different subsystems are known, monitoring strategies should explicitly develop the means to track these factors. Of particular concern is whether thresholds

crossed at one subsystem or scale will manifest themselves in a regime shift within another subsystem or scale. Consideration should be given to monitoring indicators of overall system stress as these changes may be indicative of regime shift. Because agencies and institutions have different management mandates, there can be a focus on particular resources, subsystems, and scales of interest to the exclusion of others. To overcome their sole foci, better information sharing and integration can help to improve the understanding of thresholds, identify the spatial and temporal scales at which they might occur, and detect whether threshold changes at one scale are manifested in system reorganization at another scale.

- *Develop scenarios of the consequences of alternative management options.* In some cases, the kinds of external factors that can precipitate threshold changes are well known, and furthermore are known in advance (e.g., storms, wildfire, or invasive species). In these cases, scenario analysis is a powerful tool for predicting and understanding the potential consequences of specific management actions. Scenarios should be cast at the native resolutions that make a difference to managers.
- *Match scientific research to the needs of decision-makers at multiple scales.* Much of the recent information on climate change impacts suggests that changes are occurring more quickly than forecast only a few years ago. It is also apparent that many changes are causing secondary, or cascading, domino-like, changes in other parts of the system. Management policies that were developed during relatively stable climate conditions may be inadequate for a variable world with more surprises. A shift toward multiple scales of information integration and subsequent decision-making can enhance and leverage existing management resources and approaches.

3.3. CHANGING ARCTIC TERRESTRIAL ECOSYSTEMS AND THEIR IMPACTS ON THE EARTH SYSTEM

RECOMMENDATIONS

- *Conduct research that focuses on understanding the mechanistic controls over processes that operate at different spatial and temporal scales.*
- *Develop observational networks designed to address the challenges of scaling in space and in time.*
- *Facilitate research that focuses on representing processes that operate at finer spatial scales into models that are used as tools to address questions at coarser scales.*

SCIENCE CONTEXT

High-latitude terrestrial ecosystems occupy approximately one-fourth of Earth's vegetated surface. Substantial climatic warming has occurred across the high-latitude landmass during the latter half of the twentieth century, and evidence continues to mount that this warming has been affecting the structure and function of terrestrial ecosystems in this region. It is important to understand these changes because they may have consequences for climate system functioning, particularly in the way that (a) greenhouse gases are exchanged with the atmosphere, (b) water and energy are exchanged with the atmosphere, and (c) freshwater is delivered to the Arctic Ocean. The exchange of greenhouse gases and the delivery of freshwater to the Arctic Ocean are processes that could directly influence climate at the global scale, while the exchange of water and energy has implications for regional climate that may in turn influence global climate.

To understand how responses of terrestrial ecosystems will influence the climate system of the future requires integrated understanding of how terrestrial ecosystem processes will control feedback pathways that influence the climate system. Arctic terrestrial ecosystems influence the climate system through both direct physical feedbacks of changes in snow, ice, and hydrology and through ecosystem processes that are characterized by active biotic control (**Figure 3.1**). Despite the diversity of feedback loops and

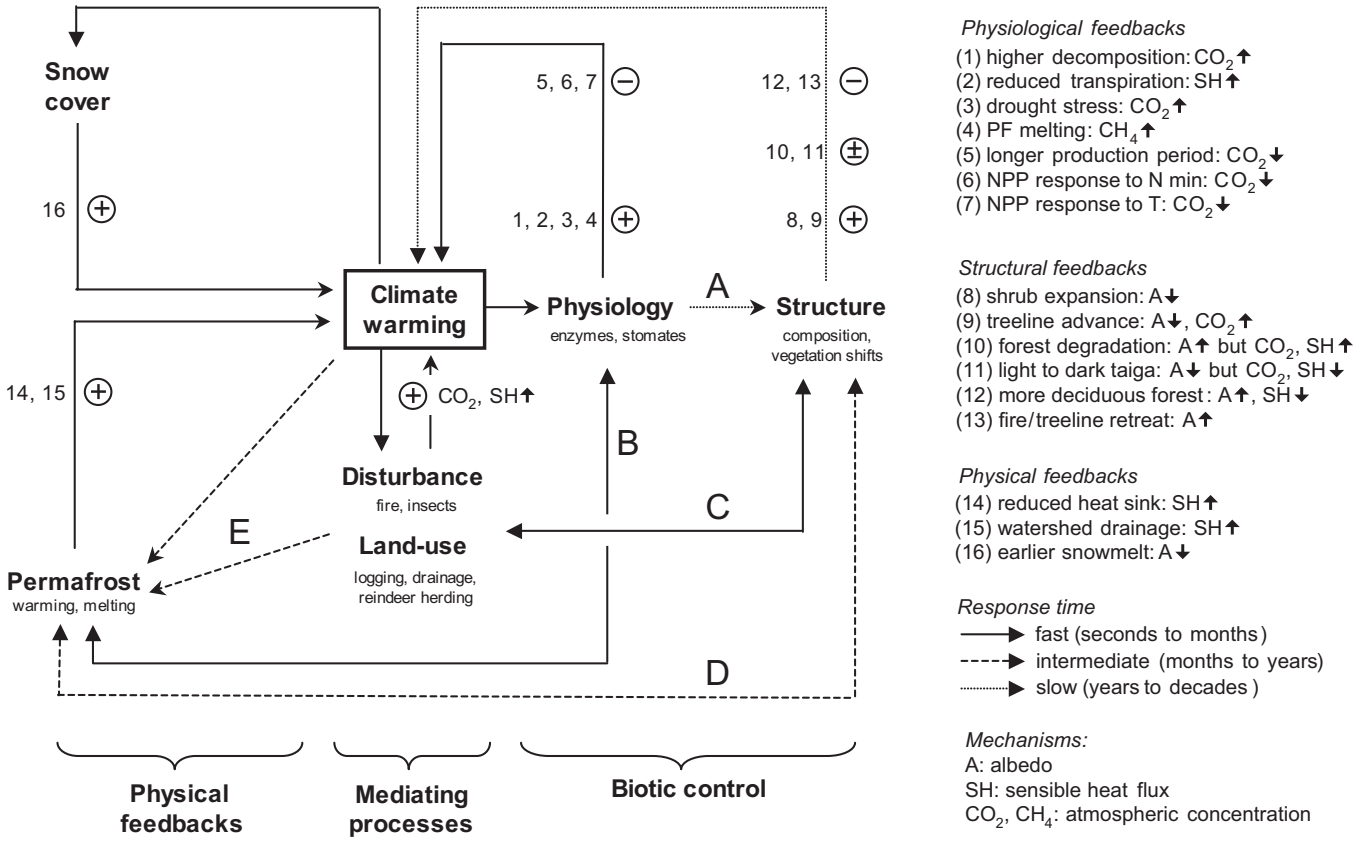


Figure 3.1. Terrestrial responses to warming in the Arctic that influence the climate system. Note the strong interconnectivity, which implies that change in one component has the potential to reverberate throughout the system. Responses of permafrost on the left are coupled with functional (physiological) and structural biotic responses on the right either directly (arrows B and D) or through mediating processes of disturbance and land use (arrows C and E). Functional and structural biotic responses are also coupled more directly (arrow A). Response pathways are identified at three time scales (seconds to months, months to years, and years to decades). Physical responses will generally result in positive feedbacks. In general, functional responses of terrestrial ecosystems act as either positive or negative feedbacks to the climate system. In contrast, most of the structural responses to warming are ambiguous as they result in both positive and negative feedbacks to the climate system. Each of these coupled subsystems have unique scaling challenges as discussed throughout **Section 2**. *(From McGuire et al., 2006)*

processes within terrestrial ecosystems, only a few terrestrial features determine the coupling of Arctic ecosystems with the climate system: (1) albedo, (2) energy partitioning (i.e., the degree to which evaporative cooling or permafrost dynamics influence the fractionation of ground heat flux or transfer of heat to the atmosphere as latent or sensible heat flux), and (3) the emissions of the greenhouse gases CO_2 and CH_4. Although it is clear that changes in high-latitude regions have consequences for the climate system as a whole through numerous possible pathways, we do not completely understand whether the net effect of changes to ecosystems will enhance or mitigate warming.

THE SCALING ISSUE

The exchange of water, energy, and trace gases involves high-latitude ecosystems, the atmosphere, and the ocean, which are all closely coupled. Thus, the representation of these processes requires integration of understanding from numerous disciplines, including climate science, hydrology, ecosystem physiology, and disturbance ecology. Forecasting the response of high-latitude ecosystems to global change will therefore rely on an integrated understanding of how the linkages will change across a spectrum of spatial and temporal scales. The fundamental scales were elucidated earlier for individual subsystems (**Section 2**), but quite possibly may involve new combinations of spatial and temporal scales as we analyze jointly all of the relevant components that comprise the pan-Arctic system.

The carbon cycle of the Arctic provides an example of the scaling challenges faced by the scientific community. The global land-ocean carbon sink has been responsible for taking up approximately 50% of fossil fuel emissions, and therefore any weakening of this sink has the potential to compromise policy actions aimed at mitigating the increase in the carbon dioxide concentration of the atmosphere. From an atmospheric perspective, the Arctic in recent decades has been responsible for 0 to 25% of the net land-ocean sink of carbon dioxide. These are very large-scale estimates based on changes in atmospheric concentrations integrated to scales of the Arctic Ocean, northern Asia, and northern North America. Analysis of changes in forest biomass in the Arctic based on numerous hectare-scale plots indicate that increases in vegetation carbon of the Arctic are responsible for 10–20% of the global land-ocean sink. However, the land-based studies really have no reliable information on how soil carbon in the Arctic has changed in recent decades. To complicate matters, remote-sensing studies indicate that photosynthesis in Arctic tundra is increasing but that photosynthesis in Arctic boreal forests is decreasing. There is a clear need to reconcile the information from these different approaches and scales to reduce the uncertainty about the role that the Arctic is playing the global land-atmosphere carbon sink.

There are similar needs to reconcile the approaches and scales of atmospheric, surface-based, and remote-sensing estimates of methane and water/energy exchanges between the surface and the atmosphere. Strategically enhanced observational systems that are designed to reduce uncertainties, measure the effects of mechanisms not effectively considered, and enhance an understanding of the scales of variability will improve the data for scaling and the ability to reconcile analyses conducted with different approaches and at different scales.

In some cases, emerging technologies may need to be employed to bridge scales. For example, the current atmospheric analysis of carbon dioxide exchange could be greatly enhanced by mesoscale atmospheric simulation supported by tall tower and continental-scale airborne campaigns. But such campaigns need to be coupled with information from other approaches to understand the mechanisms responsible for observed patterns of change.

WHAT IS REQUIRED FOR PROGRESS

- *Conduct research that focuses on understanding the mechanistic controls over processes that operate at different spatial and temporal scales.* Whether the response of terrestrial ecosystems of the Arctic will enhance or mitigate climate warming is highly uncertain. This uncertainty can potentially be reduced through integrated studies that (1) link observations of terrestrial dynamics related to climate feedbacks to the processes that are likely to influence those dynamics, and (2) incorporate the understanding gained from integrated studies into both uncoupled and fully coupled climate modeling efforts.
- *Develop observational networks designed to address the challenges of scaling in space and time.* Scaling is a key challenge to designing integrated studies that link observations and processes of terrestrial climate feedbacks, which are traditionally conducted at relatively fine spatial and temporal scales. This must be executed in a way that the understanding can be transferred to models that operate at coarse spatial and/or temporal scales. Design work on the Arctic Observing Network currently underway (AON Design and Implementation Task Force) is apropos in this context.
- *Facilitate research that focuses on representing processes that operate at finer spatial scales into models that are used as tools to address questions at coarser scales.* This upscaling re-asserts itself and must find its way into the dialogue on coupled modeling. The approach must be guided by similar principles as treated earlier in **Section 2.2.1** on weather and climate prediction, including the application of effective parameters, the use of synoptic-scale remote sensing in conjunction with modeling, the specification of reliable initial conditions for ecosystem models and associated uncertainties, and extrapolations of site-specific information. This argues for coincident interdisciplinary measurement campaigns.

4. THE ROLE OF SCALING IN SOCIETAL APPLICATIONS

4.1. INTRODUCTION

The large number of examples in **Sections 2 and 3** paints the picture of an Arctic experiencing rapid, arguably unprecedented, and ongoing environmental change. Such change, from a biogeophysical perspective, cascades into many domains—land and coastline permafrost degradation, sea ice retreat, winds and waves leading to coastal erosion, changes in vegetation, longer ice-free seasons, "greening" of the Arctic, waterlogging of soils, more variable weather, including extremes of cold or warm, icing, flooding, droughts, and increased incidence of fire. These linked changes in the Arctic environment are fundamentally interdisciplinary in nature and require system-level, synthetic, and multiscale thinking.

But the change also reverberates into many societally relevant domains: damage to and loss of 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, sea ice retreat leading to coastal erosion, fires and smoke affecting navigation and infrastructure, pest outbreaks, and loss of species, including traditionally hunted/fished species. Although there will be many, clearly positive, effects, including access to ocean shipping, resource extraction, and new fisheries, preliminary assessment indicates substantial negative impacts from climate change alone—of billions if not tens of billions of dollars for the State of Alaska to year 2030. Such estimates are generated by extrapolating site-specific damage assessments through spatial extrapolation to the domain of the entire state—fundamentally a scaling issue, but one with substantial uncertainty surrounding it, as will be discussed below.

It is thus 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 climate change adaptation can be based. Focus again will be on climate change, as an overriding backdrop of Arctic system change and as a principal forcing that will challenge policymakers and managers. Seven societal applications are presented: Arctic human health, climate change mitigation and adaptation, infrastructure at risk, subsistence fisheries, non-renewable resource extractions, sea ice navigation, and oil spill response and restoration.

4.2. ARCTIC HUMAN HEALTH RESEARCH ISSUES IN ALASKA

RECOMMENDATIONS

- *Develop a common set of core health status metrics among Arctic communities that allow comparability of populations.*
- *Develop common monitoring protocols for human tissue contaminant and zoonotic disease prevalence across contiguous international regions.*
- *Develop a common statistical approach to the scaling challenges of small populations with multiple exposures and multiple confounders.*
- *Mitigate scaling issues by creating a combined international indigenous population cohort in the Arctic in a longitudinal prospective study.*

SCIENCE CONTEXT

The United States, Canadian, and Greenlandic circumpolar regions are sparsely populated, with few large cities, and a large number of indigenous residents who are predominantly located in very small, isolated, remote communities. These remote rural residents have unique dietary exposures, ranging from the dietary benefits of a traditional northern marine subsistence diet, to an industrially produced food supply with anthropogenic food-chain contaminants, which result in substantial health status disparities. In addition, the circumpolar regions of the Western Hemisphere have experienced the most rapid increase in mean temperature in North America. Alaska's uniquely Arctic health issues center around its rural inhabitants, who are mostly Alaska Natives, and around the 40-year warming trend, seen as a 0.5–1.0°C per decade warming trend in average winter temperature. This has greatly altered lifestyles, including food acquisition from Arctic ecosystems. These many factors combine to create a unique need, and opportunity, for health research conducted at all scales, but particularly at large scales, over an observational time horizon long enough to detect distinct trends.

In human health research, large-scale data analysis provides the basis for the majority of individual, small-scale health guidance recommendations, and also drives small-scale individual patient research. Ultra-small-scale (molecular) research is most often used to develop hypotheses that drive large-scale, population-based research intervention trials.

Small remote populations are challenging to study and often require regional and sometimes international cooperation to achieve adequate sample size. Yet, one advantage to studying these populations is that in the United States, Canada, and Greenland, indigenous residents have federally financed health care systems, with unitary medical record systems and centralized data systems, which simplifies long-term follow-up and large-scale analysis of trends in health status.

Alaskan Arctic health research falls into two general categories: that associated with the changing climate, and that associated with the isolated, subsistence-dependent Alaska Native residents of rural Alaska, with some overlap between the two groups. These two groups will be briefly discussed separately in the sections that follow.

Alaska Winter Climate Warming

Emerging zoonotic diseases are potentially a major threat, due to the ability of infecting organisms to survive in warmer temperatures, as well as in-migration of new species with endemic diseases. Large-scale regional detection, surveillance, and adaptation strategies are required for these emerging threats, while the emerging infections are still confined to wildlife.

Unique Indigenous Health Problems

For unknown reasons, the incidence of colorectal, breast, and prostate cancer are rapidly rising in Alaska Native populations. This broad-scale population health disparity may have environmental and genetic etiologies, and needs population (large-scale) down to molecular (fine-scale) research. Exposure to certain compounds at critical stages of pregnancy can result in developmental abnormalities in the infant, which may only appear later in life. In very early pregnancy, certain exposures can "silence," or activate, the expression of certain genes, without changing the base-pair structure of the gene. These changes in gene activity result in a different phenotypic expression in the infant, and the change in phenotype is transmittable to subsequent generations, without a change in the basic structure of the gene. This effect is called an epigenetic effect, and may be one of the most important of any sort of prenatal dietary exposure.

The rising incidence of chronic diseases offers an opportunity for population-based, large-scale, multi-community research. The northern marine subsistence diet, which is high in omega-3 fatty acids, appears to reduce risk for certain chronic diseases such as heart disease, while organochlorine contaminants in certain subsistence species may raise risk for others such as diabetes.

Alaska Native infants have six to ten times the risk compared to U.S. all-races infants for requiring hospitalization in the first 12 months of life for severe lung infection. As a group, 85% of Alaska Natives have acquired an infection with *Helicobacter pylori* by the age of 10 years. This bacterium is associated with gastric ulcers and gastric cancer.

The Scaling Issue

There are two basic scaling issues that need to be addressed in Arctic human health research.

The most commonly encountered scaling exercise is that of attempting to statistically associate chronic low-level exposure to a mixture of toxic substances from the subsistence diet to a particular population health outcome. The usual variables in this scaling exercise are sample size (numbers of humans), and the duration of the exposure. The following problems are typically encountered:

- The sample size of the exposed population is marginal to achieve sufficient statistical power to detect significance. This issue can be addressed by combining similar populations from other regions.
- The outcome examined, for instance, subtle childhood neurodevelopmental abnormalities, may have other etiologies, called confounders, which may be present in the population, such as prenatal alcohol or tobacco exposure.
- The addition of other small populations to a small sample may introduce the effect of genetic differences that can affect the sensitivity to toxins, as well as differences in amounts and types of toxins in a different region, so that populations may not represent useful additions to a small sample.

The second type of scaling exercise considers Arctic health outcomes with time and space as the variables, as applied to various types of disease-causing exposures. Useful spatial intervals in this construct involve human population space requirements, varying from the individual, through the family, community (from very small to a small city), to an eco-region, which tends to be the defining space for the wildlife and subsistence species that provides the benefits, and exposures, for the population occupying the space. Key temporal intervals chosen reflect the rate of disease development, depending on the cause, or the time required to see the benefit of interventions. Many negative impacts have both an acute and chronic phase, as do benefits from micronutrients. Pregnancy represents a specific interval, and both negative and positive impacts can take a lifetime to develop. As described earlier, epigenetic effects can persist over generations, without a genetic change. These scaling issues are represented in **Figure 4.1**.

In summary, Arctic health research in Alaska is needed on all scales, especially initial large-scale population research (and would be productive) given the unique risk factors (climate, diet/contaminant exposure), unique disparities (certain cancers, infectious disease), and unique risk reduction factors (diet). These topics could be pursued to advantage with Canada and Greenland (Denmark) and need to be carried out prospectively.

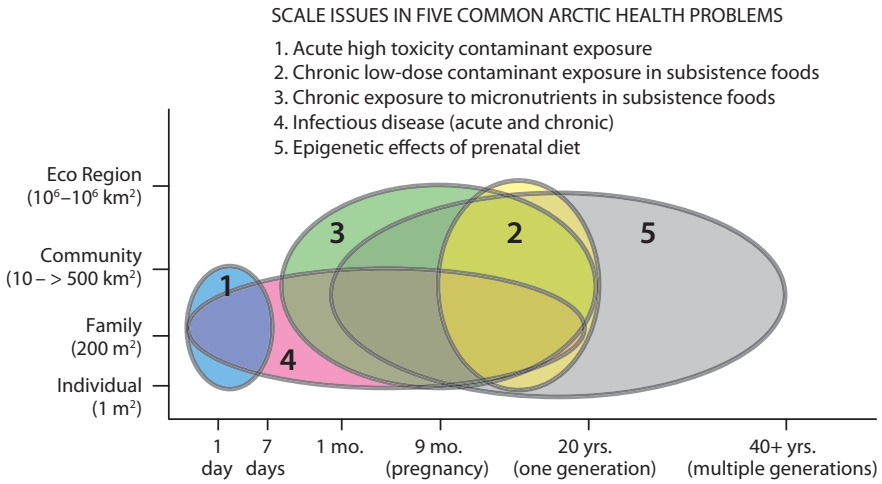


Figure 4.1. Key space-time domains in Arctic health research.

What Is Required for Progress?

- *Develop a common set of core health status metrics among Arctic communities that allow comparability of populations.* Common metrics would make health status comparison among Arctic countries feasible, and would greatly facilitate organizing large-scale international research on the impact of contaminants and micro-nutrients on health. Also, standardizing the definition of certain types of diseases would make international research on interventions easier and more meaningful.
- *Develop common monitoring protocols for human tissue contaminant and zoonotic disease prevalence across contiguous international regions.* Common elements in community monitoring protocols will ensure that data can be used to look at gradients of change in key parameters across the Arctic. Communities will, in addition, develop monitoring elements that represent local features or threats that are not shared across the network of monitoring sites.
- *Develop a common statistical approach to the scaling challenges of small populations with multiple exposures and multiple confounders.* Development of a set of common statistical methods for dealing with small, sparse data sets, with exposure elements that co-vary, would enable observations and epidemiologic analysis to proceed in comparable ways in different exposure eco-regions.
- *Mitigate scaling issues by creating a combined international indigenous population cohort in the Arctic in a longitudinal prospective study.* Minimizing scaling issues by creating multi-cohort prospective population studies, with common data points, will permit better information on the risks and benefits of traditional and modern diets over the life span to be obtained.

4.3. CLIMATE CHANGE MITIGATION

Recommendations

- *Develop Earth system models that effectively deal with the scaling issues involving the important processes that affect carbon dynamics in the Arctic.*
- *Develop integrated assessment models that can merge the understanding from fully coupled Earth system models with Arctic-initiated climate change mitigation actions at local to global scales.*

Science Context

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional manifestations of global climate change. Climate change and its impacts are apparent now throughout the United States, including most prominently Alaska. It is clear that the recent warming in the Arctic has been affecting a broad spectrum of physical, ecological, and human/cultural systems. In Alaska, climate change has been linked to increases in the frequency of insect outbreaks and wildfires, declines in lake area, thawing permafrost, increases in the risk of coastal storms to villages and fishing fleets, and the displacement of marine species and associated effects on important commercial fisheries. Arctic responses to climate change may not be restricted to adaptation alone, and Arctic societies could be at the forefront of efforts to mitigate climate change.

Climate change mitigation has traditionally been defined as the implementation of policies to reduce greenhouse gas emissions and enhance sinks for greenhouse gases. Effective climate change mitigation is important for avoiding changes to climate that impact human society. Climate change mitigation concerns itself with the following five questions:

1. *What can be done to reduce or avoid the threats of climate change?*
2. *What are the costs of mitigation actions and how do they relate to the costs of inaction?*

3. *How much time is available to realize the reductions needed to stabilize greenhouse gas concentrations in the atmosphere?*
4. *What are the policy actions that can overcome barriers to implementation?*
5. *How can climate mitigation policy be aligned with sustainable development policies?*

In the context of greenhouse gases, mitigation in the Arctic is primarily concerned with the exchange of the greenhouse gases carbon dioxide and methane. Northern high-latitude terrestrial ecosystems are generally considered to have been sinks for carbon dioxide through their storage of large quantities of carbon in unglaciated regions prior to the last glacial maximum and in regions that have since been deglaciated since the last glacial maximum. In general, this accumulation is considered to have been promoted by cold and wet soils that inhibit decomposition of dead plant tissue that enters the soil organic matter pool. In contrast, the wetlands of northern high-latitude terrestrial ecosystems are substantial sources of methane to the atmosphere. A key question emerges: *Will the response of northern high-latitude regions to climate change be the release to the atmosphere of large volumes of carbon stored over millennia as either carbon dioxide or methane?* Enhanced releases of carbon dioxide and methane could occur through a number of responses in Arctic terrestrial and marine systems (**Figure 4.2; Figure 3.1**). The answer to this question is very relevant to global mitigation efforts to stabilize greenhouse gas concentrations of carbon dioxide and methane, as it affects question number 3 above: *How much time is available to realize reductions needed to stabilize greenhouse gas concentrations in the atmosphere?*

Besides the effects of climate change on the emissions of carbon dioxide and methane in the Arctic, it is important to understand how responses will also influence water and energy exchange feedbacks. For example, it is possible that the northward migration of the treeline into existing tundra regions might promote carbon storage, which would be a response that would tend to mitigate climate change. However, the lower albedo of forest ecosystems results in more absorption of solar energy than tundra, which will tend to increase surface warming more than it is mitigated by the storage of carbon. Thus, any analysis of the responses of carbon dioxide and methane dynamics also needs to consider how functional and structural ecosystem changes associated with these dynamics will influence the full suite of feedback pathways involving the climate system.

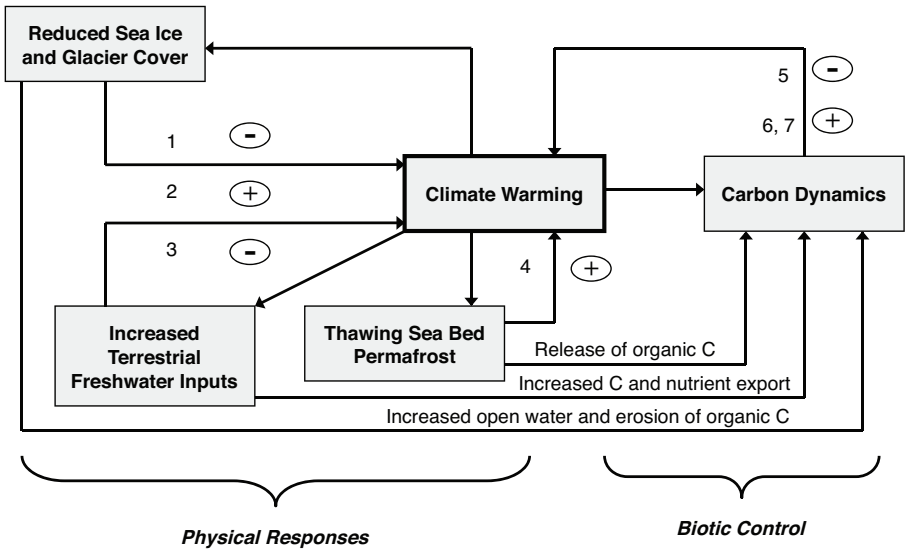


Figure 4.2. Marine carbon responses to warming in the Arctic that influence the climate system. Responses of sea ice, glaciers, and sea bed permafrost (on the left) are coupled with biotic responses (on the right) through several mechanisms affecting carbon dynamics The scales discussed throughout **Sections 2** and **3** become relevant to the understanding of Arctic climate dynamics and links to the carbon cycle. *(Modified from McGuire et al., 2006)*

The Scaling Issue

As indicated earlier, it is not clear if the response of high-latitude Arctic ecosystems will enhance or mitigate climate warming. We reiterate that scaling is the key challenge to designing integrated studies that link observations and process experiments of terrestrial and marine climate feedbacks in a way that the understanding can be transferred to models that operate at coarse spatial and/or temporal scales (see recommendations in **Sections 3.2 and 3.3**). Assessment of terrestrial carbon dynamics (**Figure 3.1**) requires simultaneous consideration of the scaling challenges in the atmosphere (**Figure 2.1**), permafrost and snow (**Figure 2.4**), and terrestrial and freshwater ecosystems (**Figure 2.14**). Assessment of marine carbon dynamics (**Figure 4.2**) requires simultaneous consideration of the scaling challenges in the atmosphere, glaciers, and ice sheets (**Figure 2.3**), sea ice (**Figure 2.10**), Arctic oceanography (**Figure 2.11**), and Arctic marine ecosystems (**Figure 2.12**). These scaling challenges are further complicated by the need to consider land-ocean exchange of water, carbon, and other biogeochemical constituents as well human actions at local, regional, national, and global scales. Assessment of the Arctic's full land-ocean carbon cycle requires progress in the development of fully coupled Earth system models that effectively deal with the scaling issues involving the important processes that affect carbon dynamics in the Arctic. Assessment of the role of humans requires integrated assessment models that can use understanding from fully coupled Earth system models to address the five questions presented above, particularly as these questions relate to human communities in the Arctic.

What Is Required for Progress?

- *Develop Earth system models that effectively deal with the scaling issues involving the important processes that affect carbon dynamics in the Arctic.* As indicated in **Section 3.3**, to better understand the sensitivity of the Arctic's carbon cycle requires an integrated approach to research that focuses on incorporating the understanding gained from observational and process studies across a spectrum of spatial and temporal scales into uncoupled models of the carbon cycle of the Arctic. The incorporation of this information requires the implementation and testing of scaling approaches, which is generally most efficiently accomplished with uncoupled models. Such comparisons between scaling approaches and the information from large-scale and long-term hierarchical observational and process-study networks may yield new insights into the scales at which processes operate, and identify new processes that need to be considered at particular scales. Once this insight is achieved in regional applications of uncoupled models, it can be more efficiently incorporated into fully coupled carbon-climate models of the Earth system, which can more confidently explore the consequences of how responses of the Arctic's carbon cycle may influence the global climate system.
- *Develop integrated assessment models that can merge the understanding from fully coupled Earth system models with Arctic-initiated climate change mitigation actions at local to global scales.* Integrated assessment models have been developed to examine the potential of human activities to mitigate climate change through a variety of possible actions, including energy efficiency, use of biofuels, and carbon sequestration activities, and to explore the implications of such actions for the five questions presented above. Most of these analyses to date have considered human activities outside the Arctic as being important to carbon mitigation and have explored the five questions in relation to human communities across more populated and industrialized parts of the world. As human communities in the Arctic are likely to be the first to experience the effects of climate change, it is important to understand the adaptive capacity of these communities. As adaptive capacity is pushed to the limit, we expect that human communities in the Arctic will exert some political pressure that may influence mitigation efforts by human societies at local up to global scales. It is therefore important to develop the capability to consider the role of Arctic-initiated mitigation actions in integrated assessment modeling efforts based on more fully coupled Earth system models that effectively incorporate Arctic processes.

4.4. PUBLIC AND PRIVATE INFRASTRUCTURE VULNERABILITIES

RECOMMENDATIONS

- *Assemble and maintain an Arctic infrastructure database.*
- *Research and model structural depreciation from climate change.*
- *Design risk-based scenarios estimating infrastructure life-cycle costs.*
- *Promote research into local flooding and changes to sea level.*

Science Context

Public infrastructure represents all of the man-made structures necessary to keep the Arctic functioning, including roads, bridges, airports, harbors, schools, military bases, post offices, fire stations, sanitation systems, and the power grid. Privately owned infrastructure includes residential homes and all structures associated with both small- and large-scale business activity.

All types of infrastructure are vitally important to people living in the Arctic and beyond. For example, airports allow critical goods and services (e.g., emergency medical services) to be delivered to rural areas not serviced by roads (see **Figure 4.3**). Private housing provides the basic human necessity of shelter, and a complex network of pipelines deliver in-demand commodities like oil and gas to world markets. Without infrastructure, communities would cease to exist in the Arctic and important internationally traded commodities could not be exported to satisfy market demand. Therefore, it is important to protect critical infrastructure in the Arctic from the risks associated with rapidly changing environmental conditions.

The most immediate climate-related impacts to Arctic infrastructure include permafrost instability, additional wildfire activity, and increased impacts from flooding and erosion. A preliminary analysis of this issue within Alaska found that climate change could add $3.6 to $6.1 billion—representing +10% to + 20% above normal wear and tear—to future costs for public infrastructure from now to 2030. These estimates took into account different possible levels of climate change and assume government agencies partially offset the level of risk by strategically adapting infrastructure to changing conditions. However, subsequent analyses by some of the principal researchers involved in this study found that a number of factors may have contributed to a systematic underestimate of both the dollar amount of infrastructure at risk and the statistical uncertainty of their original results. Additional risk to Alaska (and Arctic) *private* infrastructure is also evident, but there has been no effort to date to systematically quantify this vulnerability.

Assessing climate-related impacts to Arctic infrastructure requires collaboration between the empirical elements of a number of disciplines, including, but not limited to: economics, engineering, statistics, climatology, hydrology, and ecology. The issue thus entrains virtually all of the scaling issues treated in **Section 2**. Field research by *civil engineers* and *experts in permafrost dynamics* is needed to understand how the rate of structural depreciation changes with and without the effect of changing environmental conditions. *Climatologists* are needed to provide the latest information on the region's projected climate along with measures of the statistical confidence of the models. In some places, *hydrologists* are needed to understand

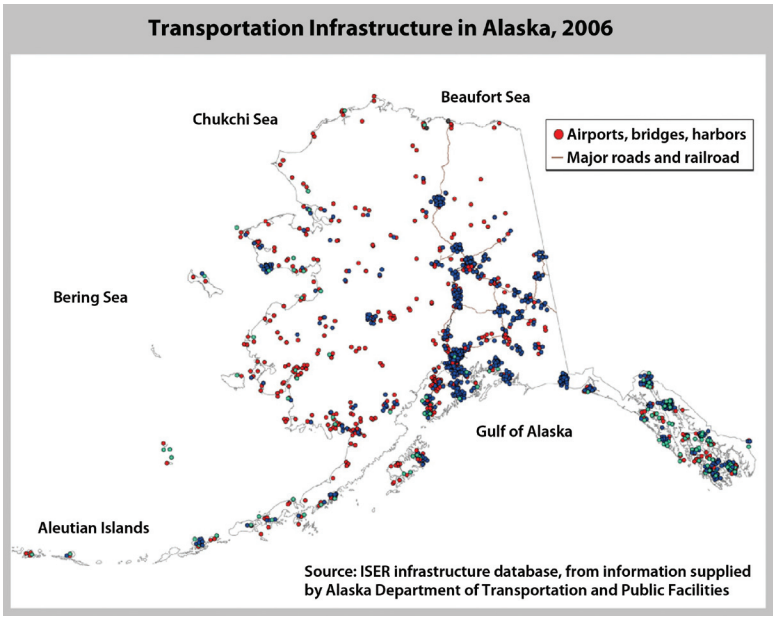


Figure 4.3. Transportation Infrastructure in Alaska. *(Larsen et al., 2008)*

the dynamics of coastal and river erosion. Urban and rural *planners* are needed to take an inventory of the region's infrastructure by location, site characteristics, and current replacement (or maintenance) cost estimates. *Economists, cost engineers,* and *actuaries* could use the information supplied by the other disciplines to estimate the future degree of financial risk for all types of infrastructure, applying a type of economic analysis known as integrated assessment modeling (IAM). *Environmental and civil engineers, materials manufacturers*, and community *planners* could then prioritize Arctic adaptation projects based on the amount of financial (and environmental) risk to each community. *Coastal* and *terrestrial ecologists* will be needed to assess both changes to wildlife habitats and subsistence food chains.

THE SCALING ISSUE

Both spatial and temporal dimensions must be considered when assessing the amount of Arctic public and private infrastructure at risk from rapid climate change.

Spatially, the proximity of infrastructure to climate-related effects like wildfire activity (see **Section 2.3.2**), accelerated shoreline erosion, and thawing permafrost highlight the challenge of having to simultaneously consider large-scale forcings in the climate domain, while at the same time analyzing depreciation and damage at highly local scales. It is clear that the more environmental factors affect depreciation of the structure, the greater the amount of financial and physical risk from premature failure. Effective long-run planning to reduce vulnerability should be based on location-specific and representative engineering case studies across the Arctic. For example, a preliminary infrastructure damage assessment estimated costs at the Alaska state level, but the authors noted that their overly generalized quantitative methods to depreciate infrastructure were not realistic and that modeling structural depreciation using site-specific information would greatly improve the accuracy of this integrated assessment model.

There is also an important time component that greatly influences how infrastructure responds to changing environmental conditions. The fundamental issues involve shifts in seasonality, freeze-thaw dynamics, weather extremes, and events like wildfires. Studies to estimate structural depreciation rates from wildfire activity, increased erosion, and thawing permafrost in the North remain in their infancy. **Figure 4.4** depicts hypothetical responses to one aspect of climate change and captures what is meant by financially quantifying structural damage. The rate of climate change over many decades influences the amount of funding needed today to adapt infrastructure

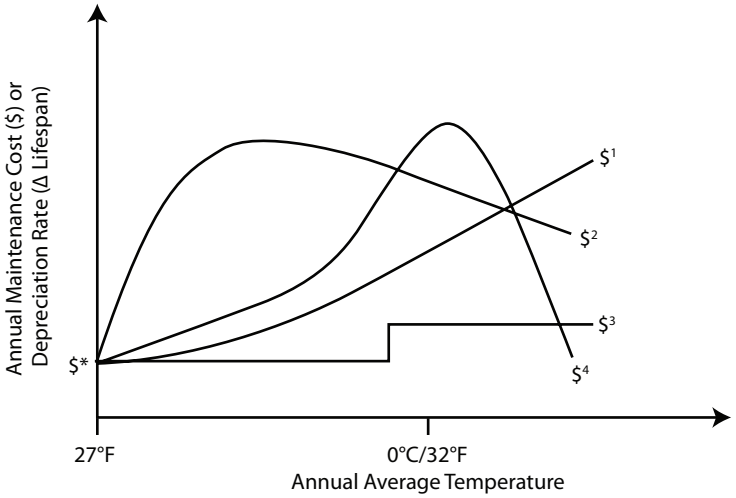


Figure 4.4. Hypothetical damage functions for infrastructure on thawing permafrost. The range of responses arise from a complex interplay of biogeophysical factors—and their rates of change—together with regional socioeconomics, and engineering, playing out at different scales. Broad-scale climate shifts must be understood in terms of their local-scale manifestations, before infrastructure vulnerabilities can be fully analyzed.

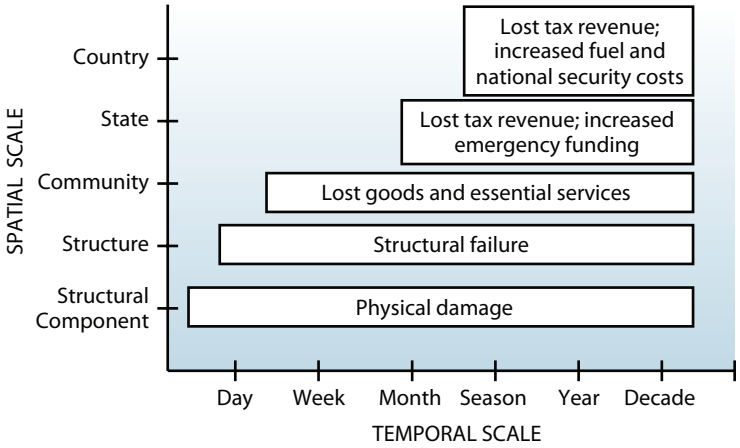


Figure 4.5. Schematic representation of some overlapping temporal and spatial scales involving infrastructure at risk in the Arctic.

to future environmental conditions. For example, a bridge that has a useful lifespan of 50–100 years may have a fundamentally different degree of climate-related risk than a road with an average lifespan of 15 years that will be replaced more frequently regardless of the changing climate. Again, estimating the financial and physical vulnerabilities of infrastructure builds on research from many different fields of study so that many of the temporal and spatial scale perspectives from the other disciplines, including uncertainties, are compounded at this level of analysis.

WHAT IS REQUIRED FOR PROGRESS?

- *Assemble and maintain an Arctic infrastructure database.* There is incomplete information on the location, age, and current value of Arctic infrastructure. The advent of Internet-based mapping tools and data sets should facilitate the much-needed merger of high-resolution socio-economic and biogeophysical data sets.
- *Research and model structural depreciation from climate change.* There is a general shortfall in applied engineering research that quantifies how specific types of infrastructure built near at-risk locations will physically (and financially) respond to significant future changes in the Arctic climate.
- *Design risk-based scenarios estimating infrastructure life-cycle costs.* Plausible scenarios are needed that can explain the full range of future infrastructure depreciation outcomes that may occur as the Arctic climate continues to rapidly change. These scenarios must incorporate a full spectrum of biogeophysical, economic, and engineering indicators, including future discount rates, structure replacement costs, depreciation rates, community-level adaptive capacity, and IPCC-sanctioned climate model emissions scenarios. The idea is to acknowledge and communicate the uncertainty inherent in modeling the futures, while encouraging decision-makers to carry out strategic planning activities now to offset any and all potential risk to community infrastructure. It is clear that information is already needed in some Arctic communities to assess the compounded likelihood of uncertainty coming from many disciplines of science.
- *Promote research into local flooding and changes to sea level.* There has been little or no applied research that details which Arctic communities may be more at risk to increased flooding and which ones will not. Localized projections for changes in sea level and river runoff vary widely based on community elevation and the effect will also depend on conditions such as, in Alaska, tectonic upheaval and local atmospheric pressure.

4.5. SUBSISTENCE HARVEST AND COMMERCIAL FISHERIES

RECOMMENDATIONS

- *Support habitat fragmentation studies to better understand the linkages between Arctic system change across spatial and temporal scales and habitat integrity and availability.*
- *Develop new inventory techniques that allow better tracking and monitoring of individual species across the spatial domain of ecosystems, including indigenous and scientific knowledge bases.*
- *Conduct research on the best means and methods for managing species that may be utilized locally but are distributed or migrate across different regions—a mobile scaling issue.*

Science Context

A changing climate may produce a number of significant changes to habitat integrity and migration patterns of both terrestrial and marine subsistence, recreational, and harvest species. On a local scale, specific habitats may be modified beyond a threshold such that a species may no longer be found there. The necessary conditions that support basic food and shelter requirements may be lost, or other species may also find it suitable and force the existing species out. At a larger scale, some migratory species may no longer be able to access suitable habitat because conditions along the travel route have changed too radically. Either case may present problems to both subsistence and commercial

harvesters because of a dwindling number or absence of desired species, and the amount of time and effort it takes to find and return with those species to a home base.

Two primary issues that deal with subsistence and commercial harvest include how best to inventory the species involved, and then deciding best management practices that would permit continued use of those species. Also at hand is the issue of how much energy one is willing to expend to harvest those species, given how often in space and time those species are available. Finding the proper balance between these issues requires input and expertise from lay and scientific audiences alike. Local inhabitants can provide much insight and knowledge about past and current conditions (habitat) and populations (numbers, locations, species). Individuals with more structured scientific background (in social, biological, and political sciences) can provide scientific and managerial knowledge that would lead to informed decisions on harvest times, locations, and bag limits.

THE SCALING ISSUE

Management of subsistence and commercial harvest of living resources engages—and in many cases transcends—several scales (**Figure 4.7**) and scale-related challenges (**Figure 4.8**). The vast majority of humans living in arctic and boreal regions depend, at least in part, on a subsistence life style, whose primary and secondary food sources consist of fish (e.g., salmon, pike, white fish, char/trout), birds (e.g., ducks, geese, swan), and mammals (e.g., walrus, moose, caribou). Although most resource use occurs at a local scale (e.g., 1–10 km), some consumers travel much farther (> 20 km) depending on the resource and the season. For example, on the north slope of Alaska, local villagers will travel along the coast and up major rivers to fish camps to catch and dry fish during the summer months; in the winter, some inhabitants will use snowmobiles to travel across the tundra for caribou or to trap small fur animals. In many cases, however, it is the resource that is more mobile, traveling across great distances to a traditional location to build up energy reserves for the coming winter, to reproduce, or to molt (as in geese).

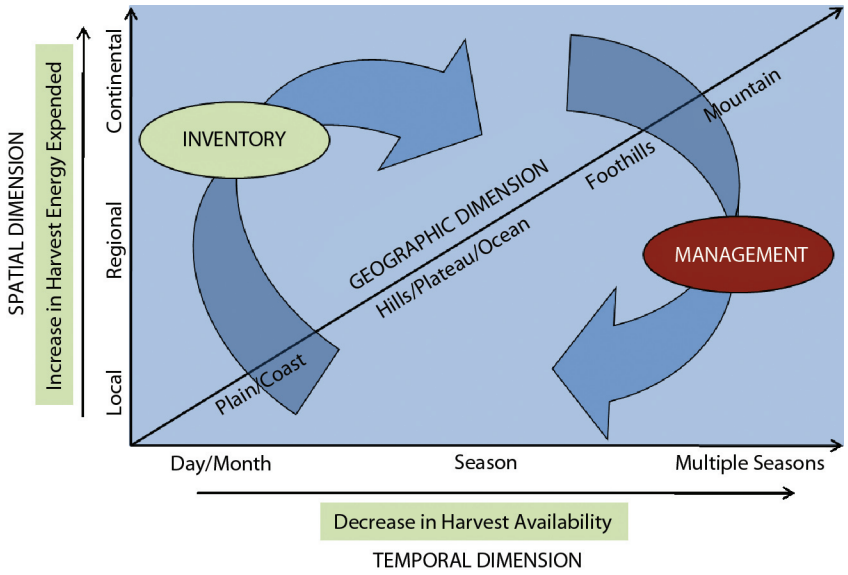


Figure 4.6. Inter-dimensional relationships of space, time, and location for subsistence and commercial use of wildlife species.

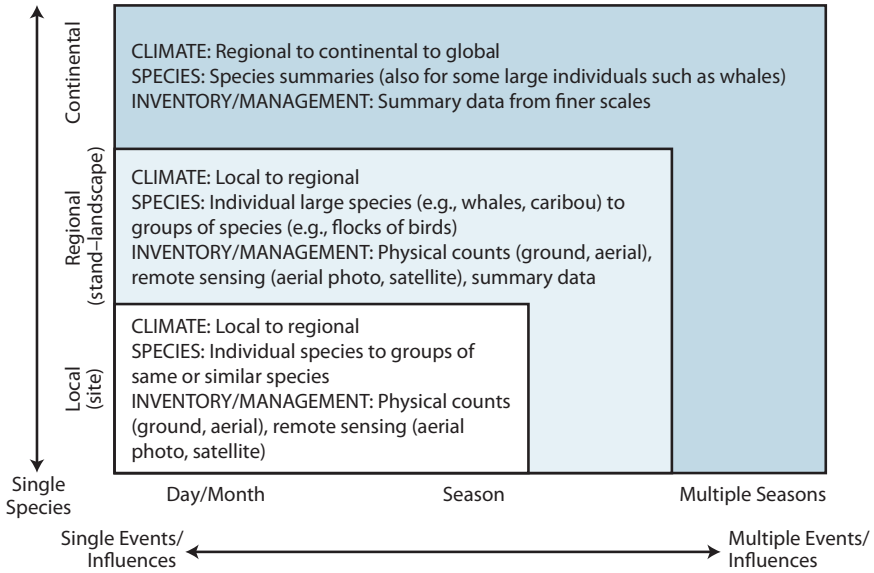


Figure 4.7. Challenges in scale occur at all levels, although each has an appropriate means to address issues using different tools.

Commercial harvest activities occur much like subsistence activities, albeit at much larger scales (space, time, duration) and normally involve one species (e.g., salmon). Commercial resource consumers (in the sense of harvest for resale) normally travel great distances to harvest a resource, even if that resource is encountered locally. For example, salmon fishing boats are normally moored at sea ports, but travel to distant bays and river outlets for the catch. For terrestrial mammal species, reindeer are currently the only commercially harvested species; in this case, more husbandry types of management and catch occur, with the animals being "moved" across large landscapes as food or habitat conditions change.

Cause and effect of different forces on subsistence and commercial harvest stocks and their inventory and management occurs at a number of different spatial and temporal scales, but not necessarily along a continuum, nor are they equal in any dimension or activity (**Figure 4.7**). This is due in part to the habitat that any individual species occupies and whether that species is found singularly or in a group. The manner by which a type of animal is harvested depends on the species, such as an individual caribou, or large numbers of fish. In addition, harvests are often targeted at explicit areas, such as a specific bay (for salmon or herring) or in the case of subsistence harvests, traditional hunting or fishing areas.

There are a number of issues that constantly need to be addressed at all spatial and temporal scales that influence the use, inventory, and ultimately the management of a given species. These issues may be different for each species or group of species. For some species, local influences directly control the numbers available for harvest and may have the greatest social, economic, and political impact, especially if the local populace is highly dependent on them for food. Inventory of these species, however, is often the easiest and least costly because they are normally harvested during a specific time period (e.g., when they are present) and are within a short distance from the point of harvest. Most Arctic species, however, are migratory and move between locations that have totally different management philosophies and modes of political governance. Inventory and management of migratory species can sometimes be easier (as in aerial surveys of herds) or more difficult (as in solitary large mammals). Because of the remote and migratory nature of these animals, overall management options may be less specific. On continental scales, although species use is conducted on a local scale (e.g., a bay for fish or specific habitat for moose), the consequences for management may cross numerous national and/or international boundaries, necessitating collegial and treaty endorsement for the sharing of population information and regulatory actions.

What Is Required for Progress?

- *Support habitat fragmentation studies to better understand the linkages between Arctic system change across spatial and temporal scales and habitat integrity and availability.* Such understanding can be fostered by research that increases understanding of minimum ecosystem function to define habitat (e.g., plant species, physical conditions, and short- and long-term climatic parameters) that allow existing subsistence or commercial species to maintain a steady state. Over the terrestrial domain, subtle local-scale changes may occur through time and space that could be linked to physics, biology, and chemistry (**Section 2.2.3 and 2.3.2; Appendix 1**), thus requiring an understanding of large- and small-scale dynamics.
- *Develop new inventory techniques that allow better tracking and monitoring of individual species across the spatial domain of ecosystems, including indigenous and scientific knowledge bases.* Research needs to be conducted on incorporating traditional environmental knowledge (TEK) about past species occurrence (e.g., numbers and spatial location), timing of arrival and departure, use of specific habitats by those species, and human consumptive use (e.g., harvests).
- *Conduct research on the best means and methods for managing species that may be utilized locally but are distributed or migrate across different regions—a mobile scaling issue.* In addition to its direct physical and chemical consequences, a changing climate also will alter vegetation patterns and hence wildlife habitat in ways that can introduce new species, force existing species to go elsewhere, or change the population of current species. The manner in which these potential changes will be distributed over space and time scales (e.g., contiguous or fragmented, disrupted regionally or only locally) is currently unknown.

4.6. NON-RENEWABLE RESOURCE EXTRACTION

Recommendations

- *Support the collection, integration, and sharing of multiscale data sets describing the inventories of current and potential stocks of various non-renewable resources.*
- *Integrate with resource inventory data the broad spectrum of environmental information that collectively represent not only the proven or potential resources, but also the spatial and temporal challenges of resource extraction in a complex and changing environment.*
- *The challenge of successfully extracting non-renewable resources economically and securing environmental protection provides an excellent opportunity to forward interdisciplinary and multiscale research.*

Science Context

Non-renewable resources are generally thought of as those that are mined with a focus on fossil fuels and minerals. Non-renewable resources could, however, also refer to the non-sustainable harvest of what might otherwise be considered a renewable resource, such as freshwater, forests, and fisheries. For the purposes of this section, non-renewable resources refer directly to the extraction of minerals and fossil fuels.

Of nearly all human activities in the modern Arctic, non-renewable resource extraction has one of the longest histories, plays an extremely important role in the economies of Arctic people, and is likely to grow in importance in the future. Oil developments on Alaska's North Slope, as well as those in Russia, Norway, and Canada, support fully regional-scale economies, and feed the world demand for energy.

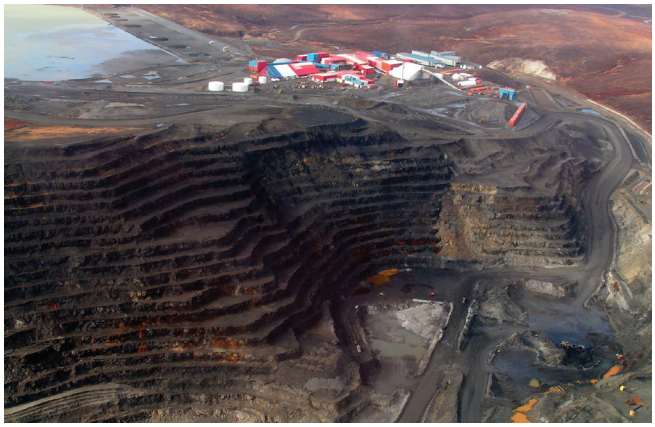


Figure 4.8. Red Dog Mine. *(Photo credit: J. Farrell)*

Before oil, however, minerals and coal extracted from the Arctic found their way to ports around the world. The Red Dog Mine, for example, is one of the world's largest producers of zinc concentrate (**Figure 4.8**). Red Dog operations contribute to Alaska's economy, creating jobs, investment, and revenue with significant economic and community benefits to Alaska's Native population. The total Red Dog operations payroll in 2007 of $48.9 million, for example, provided 475 full-time jobs for the local and regional economy. In a remote area of northwestern Alaska, this economic boost allows residents to remain in their region while maintaining a job with good pay.

The potential for summer sea travel in an Arctic with a reduced sea ice environment has spurned a "gold rush" for the oil, gas, methane hydrates, coal, and minerals that lie in the coastal shelf and on land. In this context, there are important challenges to resource exploration and development, many operating over contrasting scales. Although the intent might be to secure and transport non-renewable resources as effectively as possible from the site of extraction to delivery point, the lessons of the Exxon *Valdez* oil spill or current BP *Gulf Horizon* disaster teach us that these resources can be highly mobile and increase the scale of interest through one unfortunate accident.

Due to its harsh, remote, and often inaccessible nature, some of the most basic information needed for the exploration, exploitation, and recovery of non-renewables are inadequate and outdated. Baseline maps of the State of Alaska are out of date and for some areas have errors in the range of kilometers. In addition, significant data sets already exist that relate to resources in the Arctic. This information would be helpful to future development of the same resource for which it was originally collected or for a different one. For example, the State of Alaska is in the midst of considering gas pipeline corridors. A gas pipeline was seriously considered at least twice in the past. A consortium of companies collected data along potential corridors (across state and federal land). However, no provision was

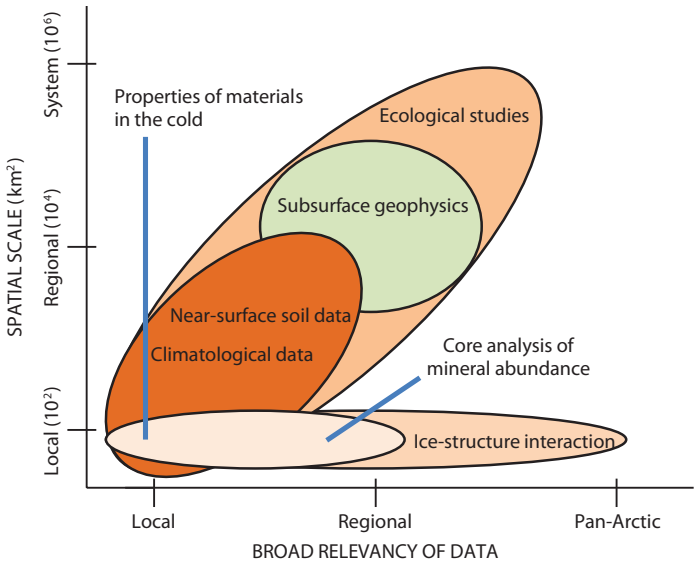


Figure 4.9. The distribution of non-renewable assets encompasses a wide range of scales and domains.

ever made that these data would eventually be made public. As such, they are not available and the information is destined to be collected once again.

Major limits on exploration and development of non-renewable resources are related to: (1) uncertainty associated with legal access to develop the resource, (2) uncertainty associated with the economic operating regime, including incentives and long-term tax structures, and (3) uncertainty associated with the engineering of extraction and transportation of the resource.

The easiest of the grand challenges to solve for a resource development company is uncertainty associated with the identification, extraction, and transportation of the resource itself. Although addressing technical issues will require a great deal of investment and data collection, this is fundamentally an issue of technical feasibility. Certainly, some issues related to development of a non-renewable resource are well known, while climate uncertainty adds a new twist. Except for future climate scenarios, where data do not exist, the technology exists to collect such data, at least to characterize contemporary climate conditions.

A slightly more difficult problem for resource extraction is understanding the future economic operating regime. Although this problem cannot easily be solved by collecting data alone, models that require data input are valuable. The most difficult major challenge is forecasting legal access to the resource. If a resource is identified and quantified, it may not be developed for reasons of legal access. This would most often result from court challenges related to potential environmental disturbance. For example, future oil and gas development in the Cook Inlet area of Alaska will be predicated on the listing of the Cook Inlet beluga whale as an endangered subspecies. Likewise, development on Alaska's North Slope is predicated on the potential listing of the polar bear. At this point, there is simply not the environmental data for the resource industries to be able to see where challenges will arise, where they are refutable, and how long challenges may last. Ecological studies are often needed before a project is started to gain a better understanding of the potential environmental issues. Environmental studies are then needed throughout the project to assess the actual and potential impacts. Often, environmental studies are needed long after a project to ensure compliance with the original operating permits.

THE SCALING ISSUE

The distribution of non-renewable natural assets encompasses a wide range of scales and domains (**Figure 4.9**). It is therefore critical that scaling issues related to the exploration for, extraction and transport of, and trading in minerals and fossil fuels be addressed. Companies around the world are investing money to extract minerals and fossil fuels from the Arctic. Private and public funding is dedicated to understanding the spatial distribution of the resource, as well as the spatial and temporal features of the environment in which resource industries operate.

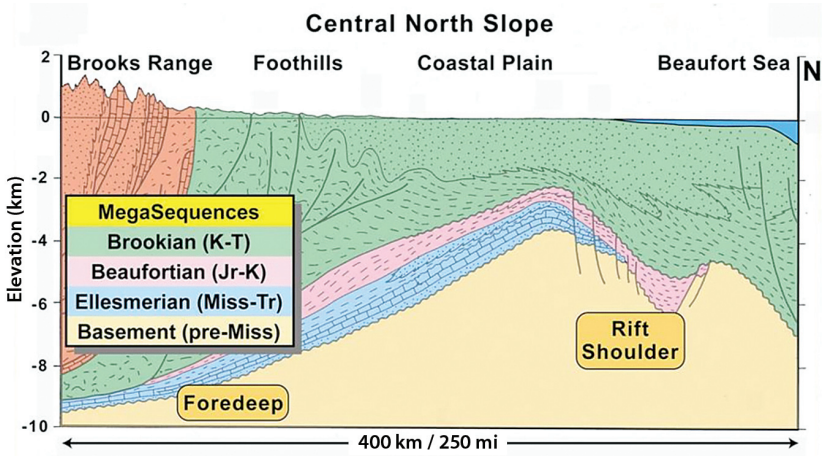


Figure 4.10. North Slope stratigraphy. *(Courtesy of Dave Houseknecht, U.S. Geological Survey)*

For most resource extraction, the exploratory process includes a broad spectrum of spatial scales, exemplified by the mapping of the subsurface that extends kilometers deep and tens-to-hundreds-to thousands of square kilometers in areal extent (**Figures 4.9 and 4.10**). At the opposite end of the spectrum, proving of the resource, microscopic gold veins in a host matrix is the spatial scale at which the highest scrutiny occurs.

From the operations standpoint, offshore oil structures and transport must be able to withstand sea ice. This requires an understanding of the regional movement of sea ice as well as its thickness, strength, and age (see **Sections 2.2.4 and 4.7**). Slightly more refined are ice-related processes such as gouging of the seafloor, and strudel scour that would reduce a pipeline's integrity. At a smaller scale, the forces of ice on structures, loading criteria, and even the microscopic contaminants in steel that make it brittle in the cold must be understood and addressed in the platform, ship, or pipeline design (**Figure 4.11**).

Resource extraction operators understand the value of the environment they operate in from an ecological sustainability standpoint. Oil and mining companies spend millions of dollars understanding the local and regional ecology and biodiversity, with the aim of ensuring that their permits to operate are fulfilled and operations do not cause harm to the environment. In this context, the many scales relevant to climate and weather (to provide for operations), ecosystems or wildlife on land and in the ocean (to ensure legal protections of the environment), all become relevant to the single activity of non-renewable resource extraction. These issues are reviewed throughout **Section 2**.

Figure 4.11. Alpine Oil Facility (ConocoPhillips Alaska) in Arctic Alaska. *(Photo credit: D. White)*

What Is Required for Progress?

- *Support the collection, integration, and sharing of multiscale data sets describing the inventories of current and potential stocks of various non-renewable resources.* Challenges associated with the Arctic being a remote, harsh, and highly seasonal system in many instances restricts access to its exploration and resource development. As a region, it is relatively data poor. In this context, protocols for sharing proprietary and public data sets become ever more important. Uniting fragmentary databases sets the stage for new research that can secure insights from the conjunction of otherwise disparate data resources. A policy that promotes more transparent access to otherwise proprietary data sets, particularly when describing conditions on state or federal lands, is in the public interest, at a minimum to avoid duplication of effort.
- *Integrate with resource inventory data the broad spectrum of environmental information that collectively represent not only the proven or potential resources, but also the spatial and temporal challenges of resource extraction in a complex and changing environment.* Resource exploration and development in the Arctic poses important challenges that are absent from more temperate settings. Strong environmental gradients, including seasonal phase changes from ice to water that limit land and marine transportation, unique ecosystem processes, and climate change argue for the integration of up-to-date weather, climate, and other environmental data sets (as for the distribution of migrating species), which currently do not exist.
- *The challenge of successfully extracting non-renewable resources economically and securing environmental protection provides an excellent opportunity to forward interdisciplinary and multiscale research.* Integrating data sets is one important objective, but falls short new integrative research. Federal and state permitting requirements that include environmental protection provisions for non-renewable resource activities represent a custom-made interdisciplinary and multiscale research challenge. How to best manage and protect other natural assets—at all scales, from borehole or mine, to watershed, to coastal shelf domains—requires knowledge across many disciplines. It also represents an opportunity to forward private-public-academic partnerships.

4.7. ICE NAVIGATION IN A CHANGING ARCTIC

RECOMMENDATIONS

- *Support basic sea ice research to increase the fidelity of estimates of the presence and character of Arctic marine ice, on temporal and spatial scales necessary for shorter-term tactical and strategic operations as well as longer-term operational planning.*
- *Promote a major structural transformation in sea ice operations through synthesis and integration of the broad suite of observational and modeling capabilities, supporting multiscale and multisensor data assimilation and simulation, from shipboard up to pan-Artic satellite surveillance domains.*
- *Improve training on advanced ice information systems that enhance human and environmental safety and promote more-efficient ship operations in the Arctic.*
- *Renew commitments to maintain U.S. polar-orbiting satellites and to usher in a new generation of radar capabilities that are in the national interest with respect to the Arctic.*

SCIENCE CONTEXT

One of the emblematic changes associated with global warming is the loss of seasonal sea ice across the Arctic ocean, and associated changes in its basic character—its longevity, shifting spatial distributions, abundance, thickness, reflectivity—over space and time. The complexity of characterizing contemporary ocean dynamics and the close correspondence of sea ice, ocean dynamics, and the atmosphere make this a particularly important challenge to Arctic system science (see **Section 2.2.4**). Aside from the important long-term role of Arctic sea ice in the Earth system, the remarkable changes observed even today in Arctic sea ice, especially the historic decreases in extent and thickness, have important implications for marine access and the duration of navigation seasons throughout the Arctic Ocean.

Figure 4.12. Image from a helicopter of icebreakers (125-m length) operating in the central Arctic Ocean through 2-m-thick, multiyear sea ice. Note the linear features (leads), melt ponds on the ice surface, and pressure ridge in the lower left extending to the top of the image. *(Photo credit: L.W. Brigham, 1994)*

One of the many challenges facing ice-capable ships is their probable encounter with a more dynamic and mobile Arctic sea ice cover (**Figure 4.12**). Modeling and scenario assessments conclude that a changing Arctic climate is likely to lead to more complicated sea ice topographies, for example, elongated ridges of sea ice that can render ship transits much more difficult and slow, and at times make passage impossible. Effective monitoring of short-term sea ice changes (within hours) and longer-term changes in the ice cover (days to weeks) is essential for the safety, reliability, and effectiveness of all future Arctic marine transportation systems. The changing nature of Arctic environmental conditions will require more timely and effective observations through a broad range of spatial and temporal scales. To this end, remotely sensed imagery of Arctic sea ice from satellites, aircraft, and ships will play an increasingly critical role in the safe and efficient movement of ships through ice-covered waters. An understanding of the range and mix of spatial-temporal scales for sea ice can be a valuable asset for mariners, ice center forecasters, ship designers, transportation planners, and others.

THE SCALING ISSUE

Ship navigation through ice generally requires three basic levels of information aboard ship, which we can consider to represent issues essentially of scale. We first have *tactical* information required for immediate navigation, such as course alteration and maneuvering. Next, *strategic* information is required for daily track planning and course decision-making. A third information class linked to scale is *operational planning*, which requires knowledge on both short and long time scales. This type information is

typically developed ashore in ice or weather centers that provide Arctic mariners with ice forecasts and generate predictions for ice conditions (days, weeks, and seasons ahead of transits), weather conditions, transit difficulty, and even optimized routes. There can be considerable overlap across the spatial scales, which reflects concepts developed further in **Section 2.2.4**. Using this nomenclature, the key sea ice and climatological parameters that are critical to ice navigation include:

- Topography (ridges, rafts, leads)—tactical, strategic
- Thickness—tactical, strategic, operational planning
- Concentration—tactical, strategic
- Floe size and small-scale features—tactical
- Snow cover—tactical
- Strength (ice age, first and multiyear ice)—tactical, strategic, operational planning
- Ice drift—strategic, operational planning
- Regional climatology (especially winds)—operational planning

Each of these variables operates over a range of spatial and temporal scales. The challenge for the ice navigators and national ice centers is to develop an integrated strategy of observations, across multiple spatial and temporal scales, with ice forecasts based on sea ice models.

Many national ice and weather centers provide large-scale and regional-scale sea ice charts and forecasting products for the Arctic Ocean. Most of the products are based on (low-resolution) satellite-derived images of the Arctic as well as information from sea ice model simulations. Passive microwave, infrared, and optical (visible) satellite sensors provide a host of imagery used to produce sea ice charts that are of strategic and operational planning use. However, ice thickness information and high-resolution information on ridging and ice floe size are not generally available. Thus, the charts are of very limited tactical use for ships navigating through ice. Discriminating between first year and multiyear sea ice has also been challenging using these sensors (although passive microwave data have been used to identify winter multiyear ice). **Table 4.1** includes selected examples of observing systems that can provide sea ice information across broad spatial and temporal scales.

The expanded use of imagery from space-borne synthetic aperture radar (SAR) sensors will provide robust sea ice information of tactical use for ice navigation in the twenty-first century. The latest SAR sensors—all active microwave (radar) sensors that produce their own energy that is reflected back to the sensor—operate in a range of frequencies and swath widths, providing information at several spatial resolutions. The SAR sensors operate in all weather and light conditions and can provide images with information on ice floes, deformed ice, ridges, thin ice, ice types, and times for ice freezeup and melt onset. One of the key challenges of using SAR information has been the development of effective and efficient methods or schemes of automatic sea ice classification. Also today, passive microwave, infrared, and visible images from satellites are increasingly used to assist in the interpretation of ice features in SAR imagery.

There is an ongoing fusion of data in the sea ice interpretation process, which will continue in the years ahead. Greater and more effective data fusion will lead to new sea ice products and ice charts that could include route optimization and ship transit difficulty information. One of the key challenges will be the integration of enhanced information on sea ice thickness potentially derived from improved satellite and airborne sensors. A key issue will continue to be the speed at which this enhanced information can be transferred from the ice centers to the ships navigating through ice.

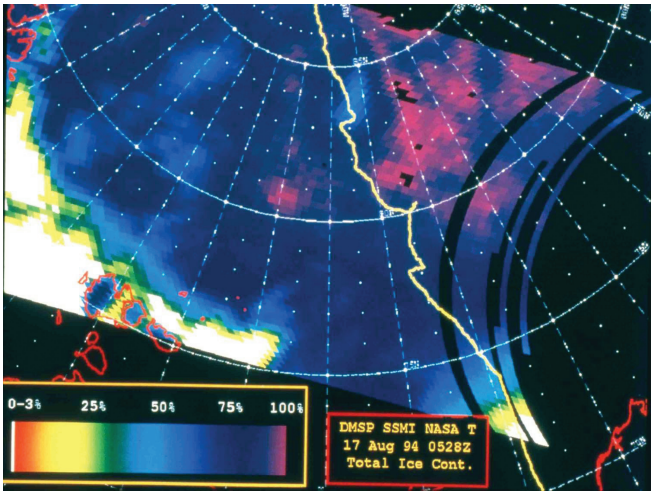


Figure 4.13. Passive microwave satellite image received directly aboard the U.S. Coast Guard icebreaker *Polar Sea* in near-real time on August 17, 1994. An algorithm converts the microwave brightness temperatures to sea ice concentrations shown in the false color scale. Note the swath (width) of the satellite pass, the ship's track in yellow, and Alaska in the lower right. The resolution of the pixels in the image is 12.5 kilometers, useful for strategic, but not tactical, navigation. *(Image from the U.S. Defense Meteorological Satellite Program)*

TABLE 4.1. SELECTED OBSERVING SYSTEMS FOR ICE NAVIGATION AND THEIR SCALE CAPABILITIES

OBSERVING SYSTEM	COVERAGE/IMAGE RESOLUTION	SCALE/DELIVERY ISSUES
Satellite systems: Low resolution *Passive microwave, scatterometers*	**Large scale: 10–50 km** *Sea ice edge, concentration, ice drift*	**Large-scale information** *Daily delivery, real-time delivery aboard ship, no thickness data*
Satellite systems: High resolution *Synthetic aperture radar (SAR), optical and infrared (IR)*	**Regional to local scale: 50 km down to 10 m** *Ice floes, surface roughness, ridges*	**Small-scale information** *Near real-time delivery from ice and weather centers, ice thickness information limited*
Airborne systems: High resolution *SAR, LIDAR, electromagnetic induction*	**Higher resolution** *Ice types, ice floes, ice roughness, ridges (height, free-board, thickness from LIDAR)*	**Small-scale information along flight paths** *Near real-time delivery*
On-ice measurement systems *Drill holes, buoys, electromagnetic induction*	**Local coverage near ship and regional coverage (buoys)** *Ice thickness, ice drift, ice temperature*	**Small-scale information** *Real-time (e.g., thickness data) from drilling, real-time from buoy information*

WHAT IS REQUIRED FOR PROGRESS?

- *Support basic sea ice research to increase the fidelity of estimates of the presence and character of Arctic marine ice, on temporal and spatial scales necessary for shorter-term tactical and strategic operations as well as longer-term operational planning.* Ice charts are the mainstay of Arctic navigation and the need for enhanced daily and weekly Arctic sea ice charts that include transit difficulty and route optimization information on a regional scale is of obvious importance in a rapidly changing Arctic sea ice domain. Verification of general sea ice charting accuracy is needed through closely coincident in situ (surface) measurements and satellite sensor observations. Indications of in situ observations on satellite-derived charts representing small-scale features not observed by satellites should be a part of this data-merging effort.
- *Promote a major structural transformation in sea ice operations through synthesis and integration of the broad suite of observational and modeling capabilities, supporting multiscale and multisensor data assimilation and simulation, from shipboard up to pan-Artic satellite surveillance domains.* Continued research into the derivation of ice thickness estimates by integrating multiple satellite data sources (data fusion) and assimilating in situ ice observations is needed. Enhancing the use of ship-based marine radar for real-time, tactical ice information (at the local scale) by requiring add-on radar processing and high-resolution display systems is also recommended. Increased repeat satellite coverage and filling spatial-temporal gaps using data fusion is needed to provide higher-frequency ice information. Continued research into airborne electromagnetic measurements of sea ice thickness for regional-scale information is an essential part of this strategy.
- *Improve training on advanced ice information systems that enhance human and environmental safety and promote more-efficient ship operations in the Arctic.* This recommendation includes the expanded use of enhanced interpretation techniques for multiple-scale sea ice data as well as the use of expert systems and other artificial intelligence technologies to improve identification of ice features.
- *Renew commitments to maintain U.S. polar-orbiting satellites and to usher in a new generation of radar capabilities that are in the national interest with respect to the Arctic.* With the disappearance of seasonal sea ice comes intensifying pressures to open the Arctic to resource extraction and navigation. Accurate detection of sea ice is part of the larger challenge of environmental surveillance to ensure territorial integrity and free shipping lanes. In particular, the essential requirement for high-resolution SAR information for navigation in ice-dominated regions remains clear. Absent commitments by the United States to invest in such systems, the nation will remain dependent on foreign sources to provide this critical information.

4.8. OIL SPILL PREPAREDNESS, RESPONSE, AND RESTORATION

RECOMMENDATIONS

- *Improve prediction of winds and currents, from small-scale coastal features (e.g., Langmuir cells in the surface mixed layer) and terrain-steering winds in areas of rugged topography to large-scale coastal processes, which can move over long distances.*
- *Provide better detection of oil in the Arctic environment, with solutions for both summer (light) and winter (dark) conditions.*
- *Conduct sensitivity tests on Arctic food webs that include experiments evaluating lethal and sublethal effects of exposure to dispersed oil, including bioaccumulation and behavioral observations.*
- *Develop more refined and verified algorithms for oil fate and transport from physical processes through biological systems at the individual and population levels.*

Science Context

Environmentally conscious oil and gas development has three temporal domains: (1) planning for development and potential accidents, (2) responding to spills, and (3) recovery and restoration of the environment after a spill, including natural resource damage assessment (NRDA). Planning must consider development in the context of the lifetimes of structural investments and climate-scale variations and other environmental conditions. In the Arctic, oil hazard research should focus on detection of spilled oil, spill trajectory predictive capability, response techniques, and oil recovery methods. Success in oil spill response in ice is contingent on *finding* and *re-finding* the oil. Detection of oil in, on, and under ice in the darkness of the Arctic winter is arguably a major operational challenge. International cooperation is required as international borders mean little as oil spills move with the winds and currents.

Figure 4.14. Prevention and Emergency Response Program (PERP) response to Kuparuk 2U Pad crude oil spill, January 5–6, 2008. Photo is of cleanup operations on January 6, 2008. *(Photo credit: J. Ebel, Alaska Department of Environmental Conservation)*

Climate change creates a moving target for planning and environmental development strategies. Monitoring rapid changes in the Arctic is key to environmentally sound oil and gas development. As the Arctic changes from a benthic (bottom) to a more pelagic (open water) dominated ecosystem under climate change, we need to continually refresh our understanding of changing ecosystems to predict the effects and outcomes of spills.

Understanding spills requires detailed interdisciplinary knowledge. During oil spill response, prediction is the focus; after the spill, hindcasting the event is required to identify the domain (i.e., scale) of impact. Predicting the physical conditions involves integration of atmospheric, cryospheric, and oceanographic information. Layering and integrating this information with oil chemistry, toxicity, and biological resources adds enormous complexity in appropriately informing decision-makers, and encompasses the scale challenges discussed throughout **Section 2**. Some of the complexity results from having both oceanic and terrestrial dimensions at work—oil spills directly into open waters (from drilling rigs and ships), onto land (oil production and transport facilities), or sometimes a combination of the two (ocean spills making landfall). Thus, the domains of impact are unique and, in some cases, are highly mobile, with the relevant scales expanding and contracting rapidly and extensively.

Data collection starts with pre-assessment information (background levels of contaminants) to differentiate effects related to oil and gas development from other anthropogenic effects in the Arctic. High-latitude surveys (over all seasons and covering large spatial extent) provide the most comprehensive information, but are difficult to finance and stage. Pre-assessment studies of baseline biological population levels provide critical input data during a spill.

NRDA involves quantifying injuries using observations of the physical environment, oil distribution, and impacts on biological resources. Modeling is used to fill information gaps, for example, based on the number of oiled birds, fish, and mammals collected, which is less than the actual number killed. Biological effects modeling requires (1) quantification of oil fates (processes like weathering, emulsification, evaporation, dissolution) under Arctic environmental conditions; (2) evaluation of exposure and dose to arctic wildlife and aquatic biota at various life stages; (3) estimation of individual effects levels and physiological response; and (4) assessment of population and ecosystem-level impacts.

Understanding water-column effects is important, particularly trophic levels below the headline species. Behavior and toxicity information is needed for biological resources in order to estimate how they could encounter oil, and how oil toxicity affects them. Within surface waters, behavior of resident invertebrates and larval fish is largely unknown. Their "encounter rate" with floating oil and dispersed oil droplets greatly influences exposure and determines the impacts from individuals to populations. Normally, toxicity is reported as median lethal concentrations after 96-hour exposures. However, this does not mimic a spill's initial spike in concentrations and often rapid decay thereafter. To address this issue, the Chemical Response to Oil Spills: Ecological Research Forum (CROSERF) has recommended refinements in toxicity test methods for Arctic conditions. Modeling algorithms need verification under arctic conditions, as the cold temperatures slow biological uptake. Toxicity effects should vary greatly with temperature and duration of exposure.

Figure 4.15. Cleanup crews at work in Skan Bay, Alaska. Photo taken January 8, 2005. *(Official Unified Command photo by U.S. Coast Guard Petty Officer T. McKenzie)*

THE SCALING ISSUE

Oil spills in the coastal environment are highly mobile and affect natural resources. The smallest scales considered are the net movement of droplets or tarballs, which affect individual animals. The largest scales are ocean currents and coastal winds that can move persistent oils hundreds of kilometers, causing ecological effects along the way. Oil spills on the water surface are unusual among pollutants because spills broken into small tarballs sometimes move into coastal convergence zones and re-coalesce into slicks. This process was seen in the T/V *Exxon Valdez* accident, where the greatest damage to bird populations occurred far from the location of the wreck.

The modern view of an oil spill slick is a continuum of droplets from tens of microns to several millimeters within an individual slick that is meters to kilometers in size. Biological interaction with a slick can occur from the smallest scale to the largest. Dissolution of toxics is faster from the smaller droplets because of the higher surface-to-volume ratio. Oil becomes entrained into food webs. Marine copepods, for example, ingest oil droplets that fall within the larger size range of their preferred food. Large slicks can contact a variety of marine animals and wildlife. Combined knowledge from these varieties of scales is necessary to accurately inform response decisions and evaluate tradeoffs.

Accurate prediction of coastal circulation is required over the spectrum of scales discussed in **Section 2.2.4**, including synoptic-scale (major fronts and weather events), small-scale (e.g., sub-kilometer) models of winds and currents, and hydrological inputs from Arctic rivers. Long, immeasurably thin convergence lines, such as the edge of freshwater outflow over seawater, can play a critical role in controlling the ultimate fate of the oil spill. Oil can be moved long distances along a convergence line, can be held off from beaching a shoreline, or collect and reform into larger slicks. Predictions and observations at all these scales are essential for successful response interventions.

In the realm of event detection and response, remote sensing is critical for detection of oil on, in, and under ice. Ground-penetrating radar is an emerging technology for the detection of oil in and under ice, but more work needs to be done to bring this technology into the field (see MMS report http://www.mms.gov/tarprojects/588.htm). Another technique for detecting oil under ice that is undergoing preliminary evaluation is nuclear magnetic resonance. Optical satellite imagery provides information on ice cover; however, satellite images arrive infrequently compared to the swift wind-forced changes in ice concentrations. Radar-based imaging has the potential to provide near-real-time ice concentration in the field, in particular from airborne platforms when the capricious Arctic weather permits.

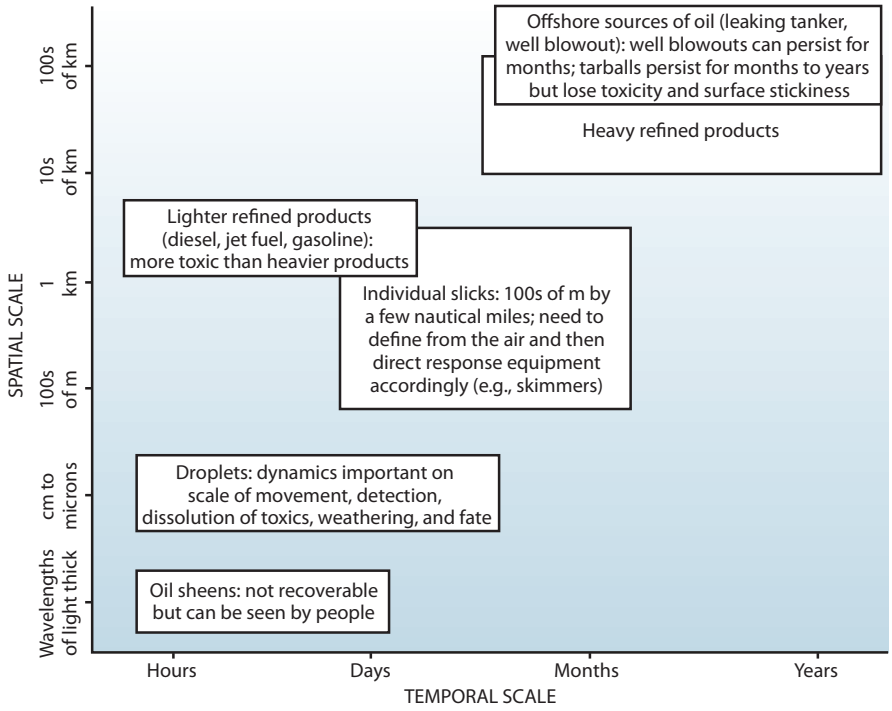


Figure 4.16.

WHAT IS REQUIRED FOR PROGRESS?

- *Improve prediction of winds and currents, from small-scale coastal features (e.g., Langmuir cells in the surface mixed layer) and terrain-steering winds in areas of rugged topography to large-scale coastal processes, which can move oil over long distances.* Numerical model results allow decision-makers to have a broader view of the spill beyond surface observations. Predicting where oil could contact the shoreline is important for staging response equipment and resources.
- *Provide better detection of oil in the Arctic environment, with solutions for both summer (light) and winter (dark) conditions.* Timely and comprehensive observational networks need to be set up to achieve this goal, relying on remote sensing of spills and ice distributions and temperatures. Systems are needed to unite optical and microwave remote sensing, together with data assimilation for nowcasting and forecasting ocean/sea dynamics.
- *Conduct sensitivity tests on Arctic food webs that include experiments evaluating lethal and sublethal effects of exposure to dispersed oil, including bioaccumulation and behavioral observations.* Laboratory and field sensitivity studies of representative life forms, like the important copepod *Calanus glacialis*, and other key species, are needed. Another sensitivity is associated with dispersed oil adhering to marine mammal skin and baleen. Determining background levels of food web contamination is needed in order to provide baseline levels for comparison during a spill.
- *Develop more refined and verified algorithms for predicting oil fate and transport from physical processes through biological systems at the individual and population levels.* Models at scales from oil droplets to surface slicks need to be integrated with chemical fate, and toxicological and biological models, that treat multiple biological scales—from bacteria that degrade oil to zooplankton that ingest oil droplets to higher trophic levels, including the capacity to assess and forecast impacts on wildlife behavior. In this way, prevention of oil contact with wildlife, and the capture and rehabilitation of oiled wildlife, could be substantially improved.

5. SYNTHESIS OF KEY FINDINGS

SYNTHESIS FINDING 1. Scaling issues and even the definitions of scale are so varied across individual disciplines that they hinder interdisciplinary research.

The organization and numerical values of the space-time scale plots presented for each of the subsections of **Section 2** amply demonstrate the great variety in scales of interest across the biogeophysical and human dimensions research communities. This diversity arises in part because the nomenclature regarding scales differs so vastly across the disciplines. The term microscale to a microbial ecologist means something radically different to an Arctic ocean sea ice modeler. As another example, fluxes of trace gases over a several hour period over a small patch of landscape (1 m^2) would constitute a macrolevel system to a microbial ecologist, yet falls off the lower spectrum of spatial scales that an atmospheric modeler would likely ever consider.

This review of scaling approaches revealed that different scientific disciplines have traditionally approached the issue of scale in very different ways. This is not surprising, given that approaches to scaling in a particular discipline have largely been molded by the domains at which measurement technologies have been applied to observe the phenomena of interest, the degree of variability of these phenomena across temporal and spatial scales, and the types of models available within the discipline, for example, contrasts between census-based human population projections and atmospheric dynamic models.

The discipline-specific approaches to scaling have led to a situation in which it has been difficult for different disciplines to effectively integrate. One way forward is to cast grand challenge research questions built around transdisciplinarity that embody multiscale perspectives to understand the current and future states of the fully coupled Arctic system, with all key natural and human components.

CHIEF RECOMMENDATIONS

- *Support further studies into the manner in which individual disciplines define and attack scale-related questions, using this knowledge to identify the key temporal and spatial scales that will provide opportunities to engage multiple disciplines in cross-disciplinary research.*
- *Promote interdisciplinary research that attempts explicitly to cross the boundaries of discipline-specific scale perspectives by organizing the work around transdisciplinary "grand challenge" questions that recognize the Arctic as a coupled physical-biological-chemical-human system.*

SYNTHESIS FINDING 2. Scale incongruities among components of the Arctic system give rise to opportunities to study intermediate scales.

Although there have been different approaches to scaling within disciplines, most generally focus on measurements that have been made at discipline-specific finer scales, which are important for understanding the inherent dynamics of processes. Single disciplines generally have turned to coarser-scale models to achieve understanding over broader domains, but typically based on fine-scale study of the underlying processes. Thus, while there has been substantial progress in studying Arctic systems over small (logistically-feasible field studies) and large domains (global climate models treating a strategic policy issue), intermediate spatial and temporal scales have received relatively less attention. However, it is precisely along the interface of intermediate scales that systems are critically defined, for example, through boundary layer fluxes linking the highly heterogeneous Arctic land surface to a well-mixed overlying atmosphere. Viewed in this way, traditional plot-level experiments of gaseous carbon exchange will fail to be relevant in the global carbon cycle research agenda unless they can be scaled-up to more regionally meaningful domains, at which point they can be engaged by the weather and climate modeling community.

Conversely, such intermediate or mesoscales provide an important perspective through which coarse-scale climate models become useful in setting the bounds of climate change impacts on terrestrial landscapes, which respond to the climate over much finer scales.

The problem also presents itself through inherent scale incongruities that actually occur in nature. Difficult numerical stability problems thus challenge models in simulating component process, such as when atmospheric winds must interface with slow-moving ocean currents that have radically different time and space characteristics. Bridging these technical limitations and ensuring stable numerical "handshakes" across these contrasting time/length scales sets the stage for robust Arctic systems models that can then be useful for informing policy decisions.

CHIEF RECOMMENDATION

- *Confirm the contention that intermediate scales over space and time are under-represented and encourage research that bridges the divide separating existing work executed at more traditional fine and coarse scales.*

SYNTHESIS FINDING 3. Thresholds are scale-sensitive and important, yet prove difficult to detect, study, and/or predict.

Threshold responses occur at the point where there is an abrupt change in a system quality, property, or phenomenon, or where small changes in a driving variable of the system produces large, persistent, and potentially irreversible responses. Thresholds essentially represent tipping points, and involve time and space "edge effects." Thus, to understand the future of sea ice, researchers must factor in the time dynamics of long-term climate warming, but also year-to-year water exchanges with the Pacific and Atlantic, polynya-open water couplings, river inputs of water and heat, and winds on much shorter time scales. All of these interact over many orders of magnitude in space and time, in which relatively fine-scale changes in driving variables can result in coarse-scale, system-level changes that bear long-term legacy effects.

A key to identification of thresholds is proper representation of interactions of processes across a spectrum of scales. Again, the intermediate scale may be critical but more work needs to be focused within this space-time domain. Nested models, as described in the weather and atmosphere section, may be useful for exploring the modeling issues associated with intermediate scales and their role in threshold responses.

CHIEF RECOMMENDATION

- *Fund process, observational, and modeling studies to explore the mechanisms by which thresholds develop and test if cross-scale issues play a prominent role.*

SYNTHESIS FINDING 4. Scales of human perception are much different than those associated with the study of natural systems.

Arctic human systems are complex and multi-faceted, encompassing both indigenous and industrial societies that vary greatly in their domains of perception and human footprints. Arctic system dynamics are conditioned around several temporal scales and give rise to a broad spectrum of perceptions, concerns, and planning/response horizons—Pacific Decadal Oscillations *versus* election cycles *versus* emergency response. Issues of vulnerability are linked to temporal and spatial scales.

Traditional societies have evolved the capacity to detect and understand the implications of Arctic system change and have adapted using strategies through which they can cope with local shortages in renewable resources, for example, engaging a much larger spatial domain for hunting and gathering that encourages a higher level of mobility. Viewed as a scaling issue, native populations have developed strategies to effectively reduce the impact of high-frequency "noise" in the landscape, by integrating their interactions over a wider domain, which tends to dampen such variations. Decision-making in industrial societies also spans many spatial scales. For example, modern-day institutional and legal frameworks can be found at individual village, provincial, national, and international levels. In an age of globalization, macrolevel decisions on the Arctic can easily fail to establish links to the biogeophysical processes operating in the Arctic itself and of relevance to people and livelihoods. Thus, improved access to Arctic resources are driven primarily by considerations of global economic development, with often little regard to implications at subsidiary scales. A prime example is the elevated levels of vulnerability from oil spills and catastrophic events on coastlines and open waters associated with increases in Arctic marine shipping. At the same time, the remoteness of the region can be viewed as an opportunity to catalyze technologies that can give Arctic residents near-real-time access to information on the changing nature of their environment, from pan-Arctic down to the very local scales where they can respond to immediate threats yet also respond to longer-term environmental change.

CHIEF RECOMMENDATION

- *Document further the perceptions of space-time domains and Arctic system change by traditional and modern Arctic communities to better understand readiness to adapt to this evolving environment.*

SYNTHESIS FINDING 5. Information has not been well structured to facilitate cross-scale studies.

The space-time domains treated in the discussion on individual disciplinary perspectives (**Section 2**) not only differ across the disciplines but even within a single one, often depicting broad and overlapping scales. In addition, there are seemingly counter-intuitive approaches to similar problems. For example, atmospheric GCMs are characterized by typically long length scales (on the order of hundreds of kilometers) yet short time scales (tens of seconds to minutes), whereas forest biological studies documenting the impact of climate change might be focused on small stands or individual trees but inventoried over seasons to multiple years. Coherent information systems are not yet in place to reconcile or at least deal with these incongruities. Furthermore, social and natural scientists organize information over very different accounting units (e.g., administrative units versus watersheds) further impeding a unified system-level picture. Jointly developing models and integrated data compendia with a broad range of thematic data sets that are spatially and temporally harmonized will allow cross-disciplinary research to be more easily executed.

CHIEF RECOMMENDATIONS

- *Support development of integrated data banks and models, which represent the collective knowledge drawn from several disciplines, spatially and temporally harmonized, and armed with data discovery tools to foster interoperability and thus improve transdisciplinary research.*

SYNTHESIS FINDING 6. Science conclusions and uncertainties require better translation into information for policymakers.

The complexity and capricious nature of the Arctic system conveys a substantial challenge to document the true degree of recent change, to place such change into longer historical and paleo context, and to design mitigation and adaptation strategies that minimize the anticipated negative consequences. This will not prove to be an easy task, as change manifests itself at several scales, over many domains, and affects several stakeholder communities, all unequally distributed. It is in this context that decision-makers and managers must operate and recognize that a particular action that targets one scale may not be wholly adequate —and in some cases detrimental—at another. An important responsibility of the scientific community is to convey not only its reasoned estimates regarding the level of Arctic change but also to assign a degree of fidelity, or conversely, *uncertainty*, to its findings. This, together with a suitable outreach effort to educate Arctic information users, will permit uncertainties to be adopted into the policy formulation process. Uncertainties in our knowledge base can be compounded when moving across scales, yet this has rarely been quantified or conveyed to decision-makers.

CHIEF RECOMMENDATIONS

- *Facilitate an open dialogue through which the decision-making community clearly articulates the space and time domains over which they need policy-actionable scientific information and through which the science community can assess their readiness to provide this knowledge.*
- *Create research opportunities across the mathematical, natural, and social sciences to catalyze methods for assessing the nature of the Arctic and its degree of change, through which scientists and assessment experts can jointly characterize the system.*
- *Create forums for an interchange among scientists, policymakers, and managers on the issue of uncertainty and how to interpret and use these estimates in a proactive and positive manner.*

APPENDIX 1. A PRIMER ON SCALING

Over the last few centuries, science has amassed an immense store of knowledge about the workings of the natural world. In terrestrial ecosystem research, this knowledge was derived from short-term studies (less than a few decades) made on small plots (less than a few thousand square meters). Because of the relatively fine-scale nature of this knowledge, it is difficult to apply it directly to address questions about processes and feedbacks acting over large regions or the entire Arctic. However, this vast store of accumulated knowledge might be brought to bear to address these coarse-scale questions if they can be appropriately scaled. The purpose of this primer is to introduce some of the fundamental concepts related to the process of scaling.

In a scientific context, "scale" refers to the characteristic distance or time over which a process acts. For example, plant photosynthesis acts on a spatial scale of a few meters over a time scale of a growing season. Migration of caribou acts on a spatial scale of hundreds of kilometers over a time scale of a few weeks. "Scaling" refers to taking a relationship or model derived from knowledge at one scale and transforming it so it can be applied at some other scale. This process of scaling has several hidden problems.

In the loose usage, "scaling" has three components: *(1) projection*, which involves a change in extent (the area or time period over which a model is applied), *(2) extrapolation*, which involves a change in domain (the range of data over which a model is corroborated), and *(3) scaling* proper, which involves a change in grain (the area or time period to which a single number predicted by a model applies). The conceptual distinction among these three components is vital to the assessment of the scaling problem because each component propagates errors differently and therefore has different effects on the resolution of the final scaled product.

PROJECTION

Spatial projections are based on a spatial model with a sub-model that is applied pixel-by-pixel (or polygon-by-polygon) to develop an output map. The sub-model should have been developed and tested at the scale of the individual pixels. The extent of the sub-model is therefore the individual pixel and by repeated pixel-by-pixel application, this extent is projected to the whole map. For dynamic models, there is also a temporal projection involving the time step-by-time step application of the model.

In many spatial-model applications, there is also an implicit projection involved if the sub-model is developed and tested at a smaller scale than the pixel, but applied to the whole pixel anyway. For example, models developed based on data from experimental plots of a few hundred square meters are often applied to pixels that are several thousand square kilometers. Thus, there is an implicit projection from the 100 m^2 plot scale to the 1000 km^2 pixel scale. This implicit projection requires the assumption that the pixel is spatially uniform in all characteristics that are important inputs to the model and that there are no plot-to-plot spatial interactions within the pixel that would influence the model output. Violation of these assumptions is probably the largest source of error in pure projections. To avoid these errors, either (1) the projection should start from a finer scale so that the sub-model is applied at the scale for which it was developed or (2) the sub-model should be scaled to the size of the pixels being used for the projection (see below).

In some cases, projection does not involve any added propagation of error beyond that inherent in the sub-model and the assumptions associated with its application at the pixel scale. The exceptions are (1) dynamic models where the outcome of the previous time step is the starting point for the next time step and (2) spatially interactive models where the output from the sub-model applied to one pixel is used as input to the sub-model applied to other pixels. In the first case, errors propagate and can amplify through time. In the second case, errors generated

at one location on the map are propagated spatially to other locations and can be amplified. Assessment of this propagation of error is difficult, but can be addressed using Monte-Carlo approaches.

EXTRAPOLATION

Extrapolation involves the application of a model beyond the domain for which it was developed and tested. For example, an ecosystem model might be developed based on data collected under current climate conditions, but applied to predict ecosystem behavior under some future, drastically altered climate. Extrapolation should, of course, be avoided if at all possible, but it is rare that a model of a system as complex as an ecosystem can be fully tested for all the conditions under which it is applied. Simulations of the long-term future are particularly problematic because it is simply impossible to run the experiments necessary to fully test an ecosystem model under all the potential combinations of future climate and CO_2 concentration, for example.

The need for extrapolation is perhaps the strongest argument for mechanistic rather than empirical modeling approaches. In a mechanistic model, equations describing individual processes are linked together to mimic the interactions among processes in the real system. The real system might be too large and respond too slowly to allow a full test of the full model at reasonable expense and in a reasonable time span. However, the individual processes respond much more quickly and can therefore be tested more fully for a broad range of conditions at reasonable expense and in a reasonable time span. In addition, a mechanistic approach can make use of the enormous amount of information already compiled in past studies of these processes.

SCALING

Scaling involves a change in grain. For example, a model developed to predict the minute-to-minute photosynthetic rate of individual leaves would have to be scaled before it could be applied to predict the daily photosynthesis of a whole canopy. The most commonly used example of the need for scaling is the so-called fallacy of the averages (**Figure A1**); for any nonlinear model, the average of the predictions of the model applied over a range of conditions is not equal to the prediction of the model applied to the average of the conditions. Thus, in the example above, the predicted average photosynthesis of all the leaves in the canopy would not equal the leaf photosynthesis predicted for the average condition within the canopy.

Predictions made ignoring the fallacy of the averages will have an aggregation bias except under very special conditions. No aggregation bias will arise if the fine-scale components function independently of one another and (1) the relationship between input data and predicted output is linear or (2) the input data is uniform across all the fine-scale components. If the fine-scale components function independently but the model is nonlinear and the input is not uniform, then a straightforward statistical scaling can be applied. The resulting scaled model will be a function of the statistical properties of the input data (e.g., mean, variance of the input).

The fallacy of the averages is only one of the sources of scaling errors. For example, it does not deal with spatial interactions among the fine-scale components or with

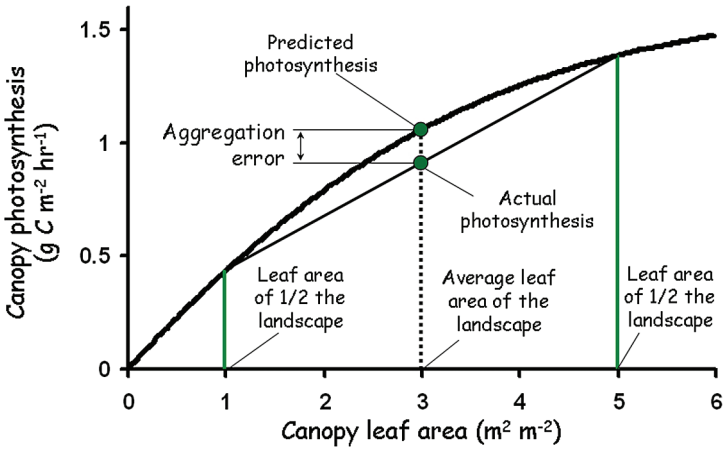


Figure A1: Fallacy of the averages. The bold black line depicts the predictions of a model relating canopy photosynthesis to the leaf area of small patches of uniform vegetation. The model had been inappropriately applied at a landscape scale. The depicted landscape is half tundra, with leaf area of 1, and half forest, with leaf area of 5. The predicted average photosynthesis for the landscape is about 16% higher than the actual photosynthesis. In the general case, a coarse-scale relationship without the bias can be derived statistically through the Expectation operator:

$$F = \int_{-\infty}^{\infty} f(x)\rho(x)\,dx$$

where F is the coarse-scale relationship, f is the fine-scale relationship, r is a probability density function describing how x is distributed. F will be a function of the statistical properties (mean, variance, etc) of how x is distributed, not a function of x itself.

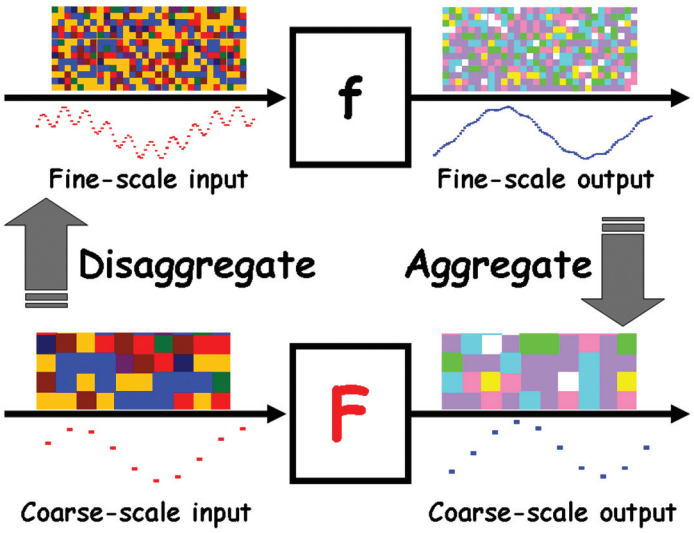


Figure A2: A general strategy for scaling. The need for scaling typically arises when a model (f) relating fine-scale process rates to fine-scale inputs is well known or easily studied, but when it is prohibitively expensive obtaining those fine-scale inputs over a large area or long time period to run the model at such a fine scale. It is then useful to scale f to derive a new model (F) that relates readily available, coarse-scale inputs to the coarse-scale process rates. In the scaling strategy depicted here, a large set of artificial coarse-scale data are randomly generated that covers all the conditions likely to be encountered when the scaled model is eventually applied. These data are disaggregated so they can be used in the fine-scale model f to generate the corresponding fine-scale output data. These fine-scale outputs are then aggregated back up to the coarse scale by averaging or summing over the appropriate area and time period. Finally, the coarse-scale model F is derived through a nonlinear regression of the coarse-scale outputs generated through the aggregation of the fine scale model simulations on the coarse-scale inputs generated to cover the desired domain of the coarse scale model. Selection of the nonlinear equations in the derived coarse-scale model is guided by knowledge of the underlying processes.

legacies passed on through time. One approach to overcoming this problem is to use Monte Carlo simulations, with a fine-scale model used to generate pseudo-data that are averaged to the appropriate coarse scale (**Figure A2**). These data are then used in a nonlinear regression analysis to infer a coarse-scale model, but with the form of the nonlinear equations being guided by knowledge of the underlying processes.

KEY TERMS USED IN SCALING

There is no standard terminology associated with scaling; different terms are applied to the same concept and the same term to different concepts. This lack of a standard has led to needless confusion. Below we define several scaling concepts and point out some inconsistencies in terminology.

SCALE: ratio of map distance to actual distance or a measure of the characteristic length over which a model operates. Cartographers define scale as the ratio of the distance on the map to the real-world distance depicted. Thus, maps representing large areas will be a small-scale maps (e.g., 1:39,370,000 = 2.54×10^{-8}) and maps representing small areas will be a large-scale maps (e.g., 1:1000 = 1×10^{-3}). The common meaning of scale is just the opposite; "large scale" refers to something large and "small scale" refers to something small. To avoid confusion, "fine scale" can be used to refer to detailed representations of small objects and "coarse scale" to refer to coarse representations of large objects. For a dynamic model, scale can also be in reference to time; a daily time step is a finer time scale than a monthly time step. Scale has two components, grain and extent (defined below).

PIXEL: uniformly sized squares (or occasionally regular hexagons) arranged on a grid to completely cover the area mapped (called a "raster-based" map). Each pixel is assigned a single value of the characteristic being mapped (e.g., for a vegetation map, each pixel is assigned one vegetation type).

POLYGON: areas of irregular size and shape arranged to completely cover the area mapped (called a "vector-based" map). Each polygon is also assigned a single value of the characteristic being mapped.

GRAIN OR SPATIAL RESOLUTION: the size of the pixels or polygons. For example, maps with 30 m spacing between pixel centers would have a 30 m grain. The grain of a polygonal map relates to the size of the smallest polygons used to tile the map. Maps can have spatial information down to a particular grain and have additional information finer than that grain, but not in a spatially explicit form. For example, a map might have information on the relative amounts of different vegetation types within each pixel, but not on their spatial distribution within a pixel. Spatial models also have an associated grain. The simulation time step defines the temporal grain of a dynamic model.

EXTENT OR DOMAIN: the total area covered by a map or the total area and time span over which a model is applied (e.g., all of the North Slope of Alaska between the years 1900 and 2100). Although there is usually a correlation between grain and extent among maps or models (small extent associated with fine grained and vice versa), there is no requirement for any relation between the two, except, of course, that the extent cannot be smaller than the grain.

RESOLUTION (see alternate definition above): the precision of the data represented by the map or model. For example, a map of average annual temperatures in 10°C increments on a grid with 10 km spacing has a resolution of ± 5°C and a grain of 10 km.

DOMAIN (see alternate definition above): the range of conditions for which a model is corroborated. A model designed and tested for wet-sedge tundra and applied to the North Slope of Alaska would have wet-sedge tundra as its domain and the North Slope as its extent. The domain might also refer to the range of input data for which the model is corroborated. For example, a soil respiration model might only be valid for tussock soils between freezing and 25°C; the domain would be tussock soils within that temperature range. For maps, the areas outside the domain are often masked out.

SPATIALLY EXPLICIT MODEL: a model that can accept spatially mapped data as an input and generates spatially mapped data as output. Typically, spatially explicit models are run at the grain of the finest-grain input map.

SPATIALLY INTERACTIVE MODEL: a spatially explicit model in which the sub-models applied to individual pixels or polygons interact with one another. For example, a hydrological model might calculate a water balance for individual pixels on a hillslope. Each pixel then requires an estimate of runoff from pixels upslope and provides runoff estimates for pixels downslope.

FRACTAL PROPERTY: a property that is invariant across scales. Fractal properties do not need to be scaled because the equations describing those properties apply to all scales.

EMERGENT PROPERTY: a property manifested at a particular scale that was unpredicted from fine-scale behaviors because of a high sensitivity to small perturbations at the fine scale and the inability to measure the fine-scale components precisely enough to discern these fine scale perturbations.

COHERENT PROPERTY: a property of particular importance to the functioning of a system that serves to define a particular spatio-temporal scale.

APPENDIX 2.
SOURCES AND BACKGROUND READING

1. INTRODUCTION

U.S. Arctic Research Commission. 2010. *Report on Goals and Objectives for Arctic Research 2009–2010.* U.S. Arctic Research Commission, Arlington, VA, 52 pp. Available online at: http://www.arctic.gov/publications/usarc_2009-10_goals.pdf (accessed June 29, 2010).

2. SCALING CHALLENGES WITHIN ARCTIC SCIENCE: A DISCIPLINARY PERSPECTIVE

2.2 PHYSICAL SYSTEMS

2.2.1. Weather and Climate Prediction

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APPENDIX 1

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ACRONYMS

ACM.....Aggregated Canopy Model
AON .....Arctic Observing Network
AW.....Atlantic Water
CROSERF .....Chemical Response to Oil Spills: Ecological Research Forum
DEM.....Digital Elevation Model
GCM .....General Circulation Model
GIS .....Geographic Information System
GPP.....Gross Primary Production
GRACE.....Gravity Recovery and Climate Experiment (NASA satellite system)
IA .....Integrated Assessment
IARPC .....Interagency Arctic Research Policy Committee
IPCC.....Intergovernmental Panel on Climate Change
LIDAR.....Light Detection and Ranging
MODIS.....Moderate Resolution Imaging Spectroradiometer (NASA satellite system)
MOS.....Model Output Statistics
NDVI.....Normalized Difference Vegetation Index (from remote sensing)
NRDA .....Natural Resource Damage Assessment
PAH.....Polycyclic Aromatic Hydrocarbons
PAR .....Photosynthetically Active Radiation
PW.....Pacific Water
SAON.....Sustained Arctic Observing Network
SAR .....Synthetic Aperture Radar
SPA.....Soil-Plant-Atmosphere complex
TEK.....Traditional Environmental Knowledge

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