<u>S</u>urface <u>T</u>ransformations in the <u>A</u>rc<u>t</u>ic <u>E</u>nvironment (STATE): Executive Summary

The surface of the arctic-- the snow, ice, vegetation and human footprint—is changing at an accelerating rate in response to global change; as the arctic surface changes, so do exchanges and transfers of energy, water, carbon, materials, and organisms (including humans) within the Arctic system. This implementation plan describes a novel research program, consisting of three major phases, designed to advance our understanding of the trajectories and impacts of those changes. The program involves both field research and synthesis in a fully integrated program; the intellectual themes linking program elements are all connected in some way to societally relevant issues. It is expected that three to five sequential announcements of opportunity might be issued to implement the proposed STATE program.

Why study the near-surface environment?
In short, we believe that the proposed program tackles the most important area of the changing Arctic. Further, we think that pressing issues related to warming and change are already emerging in the near-surface environment that make the adoption of the proposed program both timely and pressing.

- The near-surface environment is changing rapidly, and in some cases the rate of change exceeds that predicted by the best models available. Our understanding of the processes controlling near-surface environmental transformation is clearly inadequate to predict future trajectories of change.
- The near-surface environment is where people live, travel, and acquire resources; changes in the land and ocean surface have already begun to have noticeable effects on human use of the Arctic.
- Changes in the near-surface environment feed back onto the primary drivers of change (the arctic climate system and industrial development).
- Changes in the near-surface environment have important, but poorly characterized, feedbacks to the global earth system; changes in the arctic near-surface environment thus matter to residents beyond the geographic confines of the Arctic.

What is our overarching goal?

The overarching goal of the research program is to advance our understanding of trajectories and dynamics of change in the near-surface environment, and of interactions between human and bio-physical systems within the near-surface environment. In so doing, we believe we will promote innovative and socially relevant science that will enhance decision-making ability in this time of rapid change in the Arctic.

How will we ensure an integrated program with embedded synthesis?

Achieving our research goal requires the development of an integrated, synthetic, and interdisciplinary research program. Because the proposed research program emphasizes the linkages and connections between the traditional domains (land, air, ice, humans) that have in the past served as the integrating mechanism for research, alternate integrating mechanisms are needed. Here we propose to organize the research along

three cross-cutting themes, each of which is designed to help foster research of maximal relevance to society. All research done in the STATE Program will address one or more of these themes; proposers are expected to identify clearly in their proposals how their proposed research addresses one (or more) of these themes.

Theme 1: Phenology and seasonality

Changes in the timing of key biological, physical, and societal events are one of the most crucial aspects of the transformations that have occurred (and are continuing to occur) in the near-surface environment. Ecosystem functioning and human use of ecosystems often depends more on the sequence or synchrony of events than on the mean state of events. Phenology and seasonality is thus our first cross-cutting theme, which researchers can use to engage in synthesis and integration activities across projects.

Theme 2: Contingencies and uncertainty

One of the most compelling challenges to producing societally relevant research is a problem of scale: how do we downscale our understanding of the arctic system to produce locally (or even regionally) relevant/accurate predictions, and how far *can* we downscale with current tools? How do we make good decisions in the face of uncertainty surrounding local and regional dynamics? Historical contingencies that alter trajectories of ecosystem or human community development are an important source of the local heterogeneity that confounds our ability to downscale from global to local scales of inquiry. The challenge, then, is to make sense of contingencies to the extent possible, and ultimately to define the "irreducible uncertainty" in any particular linkage within the system. Contingency and uncertainty is thus our second cross-cutting theme. Like the first theme, it will serve both as a mechanism for integrating among research projects, and for synthesis endeavors that explore the theme: what is the point beyond which we genuinely can not predict system behavior? What are the consequences of irreducible uncertainty in this particular linkage for human decision-making? What new ways can we develop to deal with irreducible uncertainty?

Theme 3: Innovation and risk

The final cross-cutting theme involves innovation in response to real or perceived environmental change. Human and biological systems are not static in the face of rapid environmental change: biological communities change in composition and function, new species invade, old species may adapt, humans adopt new methods of carrying out daily tasks, adopt new technologies, and use old technologies in new ways. New and unanticipated conditions are forcing new responses for which there are no or limited traditional behaviors. The theme of innovation recognizes that human responses to environmental change are not static, nor are biological systems, and that projecting future trajectories of dynamics within either biological or human systems requires an understanding of the dynamics of innovation.

Program structure

The program itself will be structured in three phases, one leading to the next in a logical sequence. Each phase of the program contributes to achieving our overall research goal of understanding trajectories and dynamics of change in the Arctic near-surface environment. The phases build on each other, in a sequence that begins with the most pressing issue relevant to understanding the changes that will occur within Arctic system over the next several decades, and ends with an exploration of how changes in the arctic will have a profound ripple effect on the rest of the planet.

Phase 1: The central problem of the first phase of this program is to identify and understand the rates and trajectories of spatial and temporal changes—including changes in phenology and seasonality in general—in the near-surface terrestrial and marine environmental system—including changes in linkages and transfers, and to identify the contingencies and uncertainties in estimating those parameters.

Phase 2: In the second phase of the program, the focus will shift to the interactive and synergistic role of climate and development as drivers of change in the near-surface environment. Particular attention to the interactive effects of climate and development on food systems is desirable in this phase.

Phase 3: In the final phase of the program, research will emphasize the global relevance of changes in the Arctic near-surface environment by examining the linkages between Arctic near-surface change and the global climate system, global food systems, energy, etc.

Surface Transformations in the Arctic Environment (STATE): Implementation Plan

Conceptual overview

Climate warming in recent decades has transformed the combined land and sea surfaces across the Arctic, and radically altered the transfers of energy, water, carbon and other matter, as well as organisms and human phenomena and processes (information, etc.[1]) among components of the near-surface environment (which we loosely define as encompassing the land surface, the ocean/sea-ice surface, and processes occurring immediately above and below those surfaces that are relevant to regulating the state of the surface[2]; Figure 1).

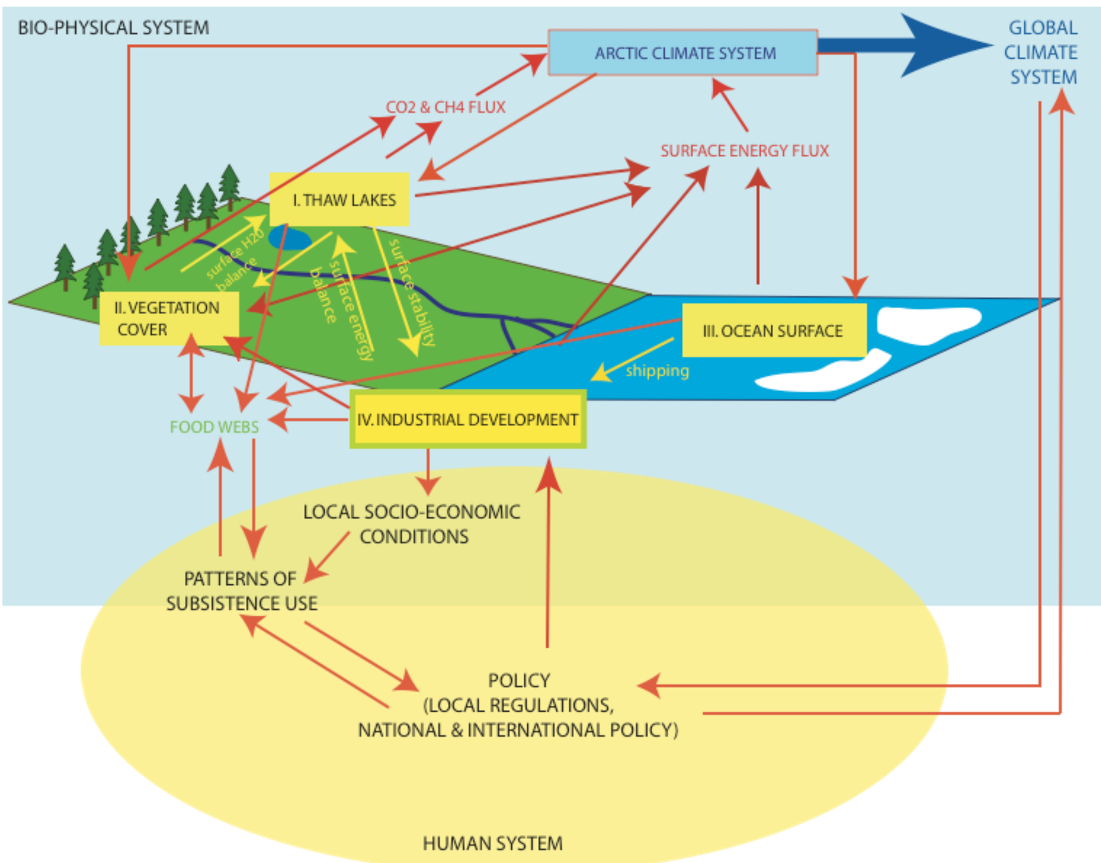

Figure 1. Schematic representation of transfers and linkages within the near-surface environment. We address different connections within this diagram at different points in the research program. The understanding of the Arctic System that informs this diagram is explained in greater detail in the prospectus that is attached as an appendix to this document.

For example, marine areas that were formerly covered by sea ice are now open water in summer; as a result transfers of heat and moisture between the ocean and atmosphere are enhanced. In the terrestrial realm, thaw lake dynamics have changed significantly throughout Alaska, Canada and Siberia as near-surface permafrost thaws and transfers of moisture between the atmosphere and the active layer, and between active layer and groundwater, are changed. Tall shrubs and trees are replacing low tundra vegetation throughout the low Arctic, initiating feedbacks on surface energy exchange that will ultimately result in enhanced surface warming. At the same time, and in part as a consequence of a warming climate, an increasing proportion of the land surface is also being transformed by industrial development, the associated infrastructure of which has significant affects on ecosystem dynamics and surface hydrology: “transfers” (movements) of humans and non-human animals, for example, are significantly changed by industrial development. These changes in the near-surface environment are both a visible manifestation and potential driver of ongoing global change across a range of spatial and temporal scales. Many of the impacts of ongoing climate change on humans – both in and out of the Arctic –are now being and will continue to be mediated by these changes in the near-surface environment[3]. Despite their importance, the collective impacts and relative importance of different drivers of change remain poorly understood. The Research Prospectus attached as an appendix to this document describes in greater detail our conceptual framework and the background thinking that informed this plan. *The overarching goal of the research program defined in this implementation plan is to advance our understanding of trajectories and dynamics of change in the near-surface environment, and of interactions between human and bio-physical systems within the near-surface environment*. Our intent is to promote an innovative program of socially relevant science that will enhance decision-making ability in this time of rapid change in the Arctic.

Integrating themes

We are proposing the development of a fully integrated program of field research other efforts to collect and generate new datasets, and ongoing synthesis, in which projects are integrated by thematic linkages. Because this research program is specifically designed to emphasize the linkages of the traditional domains (which have in the past served as the integrating mechanism for arctic research), we propose that research within this program be integrated by thematic connections among domains and research projects[4]. We have chosen three cross-cutting themes as the integrating mechanism: the three are important thematic elements of the research program because each is a crucial aspect of understanding the interactions between global environmental change and local dynamics of human systems. These themes cut across most of the broad research problems that we have identified within the overarching goal defined above. They are crucial to producing research that is of maximal relevance to society. They are also relevant to each of the traditional ARCSS domains, and thus provide a mechanism for projects operating within different domains to forge intellectual links.

Proposers will be expected to describe in explicit terms how their proposed research contributes to one (or more) of the key themes. For example, a researcher proposing to investigate the effects of changes in near-shore sea ice dynamics on marine food webs might articulate links to theme 1 (because changes in the seasonal timing of ice formation and melt are central to understanding how changes in sea ice affect marine food webs) and theme 3 (because the human response to changes in near-shore ice involves elements of risk and innovation). Those linkages should be clearly articulated within proposals. Once funding decisions are made, connections can be forged among proposals by linking proposals that speak to common themes. Those groupings will then be used as the basis for project integration and ongoing synthesis. The themes are briefly outlined below.

Theme 1: Phenology and seasonality:

Changes in the timing of key biological, physical, and societal events are one of the most crucial aspects—for humans and other organisms within the Arctic-- of the transformations that have occurred (and are continuing to occur) in the near-surface environment. Ecosystem functioning and human use of ecosystems often depends more on the sequence or synchrony of events than on the mean state of events. For example, the mean areal extent of summer sea ice may be less important to human hunters (or seals or polar bears) than the timing of formation of landfast ice in the fall, or the timing of ice break-up in the spring. Changes in mean snowfall, similarly, may be less important to industry than changes in the timing of the spring melt, which defines the end of the winter exploration season in the Arctic. Changes in seasonality are widely identified by arctic residents as being of crucial importance for human use of the arctic, and yet our understanding of drivers and consequences of phenological change remains relatively poor.

Theme 2: Contingencies and uncertainties

One of the most compelling challenges to producing socially relevant research is a problem of context and scale: how do we downscale our understanding of the arctic system to produce locally or regionally meaningful predictions, and how far *can* we downscale with current tools? How do we make good decisions in the face of uncertainty surrounding local and regional dynamics? Historical contingencies that alter trajectories of ecosystem or human community development are an important source of the local heterogeneity that challenges our ability to downscale from global to local scales of inquiry. For example, the historical accident of E.T. Barnette grounding his riverboat in the Chena River in August 1901, and the further accident that two gold miners happened to spot his trading post, initiated a chain of events that transformed the cultural and ecosystem dynamics of interior Alaska. Attempts to understand the fire regime of forest age structure of interior Alaska that failed to consider the role of that historical accident—or contingency—would ultimately fail. The challenge, then, is to make sense of contingencies to the extent possible, and ultimately to define the “irreducible uncertainty” in any particular linkage within the system. What is the point beyond which we genuinely cannot predict system behavior? What are the consequences of irreducible uncertainty in this particular linkage for human decision-making? What new ways can we develop to deal with irreducible uncertainty?

Theme 3: Innovation and risk

The final cross-cutting theme involves innovation in response to environmental changes and perceptions of those changes. Human and biological systems are not static in the face of rapid environmental change: biological communities change in composition and function, new species invade, old species may adapt, humans adopt new methods of carrying out daily tasks, adopt new technologies, and use old technologies in new ways. New and unanticipated conditions are forcing new responses for which there are no or limited traditional behaviors. The theme of innovation recognizes that human responses to environmental change are not static, nor are biological systems, and that projecting future trajectories of dynamics within either biological or human systems requires an understanding of the dynamics of innovation. Understanding how rapid change—change that is unprecedented within the cultural memory of many arctic residents—forces innovation, how innovation interacts with tradition, how larger institutions/regulatory entities stifle or promote innovation, and how innovation feeds back on arctic system change is a goal that will underlie many aspects of this research.

Program Structure

We envision that the program will consist of a series (three to five) of Announcements of Opportunity (AOs), each of which will target one aspect of understanding trajectories and impacts of near-surface environmental change in the Arctic. We have identified three major research problems within our overall research goal, and thus recommend a three-phase research program. The sequence of AOs will follow these phases, although it is possible that one Phase may result in more than one AO.

<u>Phase 1: Processes driving trajectories of change in near-surface transition zones</u>

The near-surface zone is undergoing rapid, perhaps unprecedented change. Furthermore, change is happening faster than our models predict (for components like sea ice for which good model predictions exist), so it is clear that we do not understand the processes that drive near-surface dynamics adequately. Trajectories of change are frequently non-linear, and frequently exhibit threshold behaviors (e.g., thresholds associated with the zero-degree isotherm). *The central problem of the first phase of this program is to identify and understand the rates and trajectories of spatial and temporal changes—including changes in phenology and seasonality in general—in the near-surface terrestrial and marine environmental system—including changes in linkages and transfers (characterized by Figure 1, below), and to identify the contingencies and uncertainties in estimating those parameters*. Addressing this problem will require dealing with crucial issues of extrapolation: how do we extrapolate forward from non-linear trends? How do we extrapolate among sparse networks of observations? Our goal is to improve our understanding of the near-surface system sufficiently to develop realistic scenarios of the state of the Arctic in 2050—in terms and at temporal, spatial, and/or institutional/political scales that are most relevant to human societies.

Our particular focus here is on the transition zones between and transfers among system components (the arrows in Figure 2, rather than the dynamics within the boxes). These transition zones are often key to understanding the dynamics of any particular component. For example, observations of summer thaw depth near Barrow indicate that the active layer was substantially deeper in the 1960s. Further, the same amount of summer heat input in the 1990s resulted in significantly shallower thaw depths. Clearly, the system had undergone a Markovian shift during the intervening decades. The explanation for this nonlinear response to heating lies in the dynamics of the “transient layer” between active layer and underlying permafrost. Very warm summers deepen the active layer, and facilitate transfer of moisture from the atmosphere to the base of the deeper active layer. In time, this creates an ice-enriched zone that has high thermal inertia due to the latent heat required for thaw. Additional heat energy is thus necessary for subsequent deepening of the active layer. A series of very warm summers, however, can thaw and reset the transient layer, which promotes rapid deepening of the active layer. Highly nonlinear dynamics, with unknown recurrence intervals, are thus explained by understanding the transfers of heat and moisture between the atmosphere and the upper permafrost. Many such transition zones and couplings in the near-surface environments are not adequately understood, and thus form the primary emphasis of this first phase of the proposed Near-Surface Processes research program.

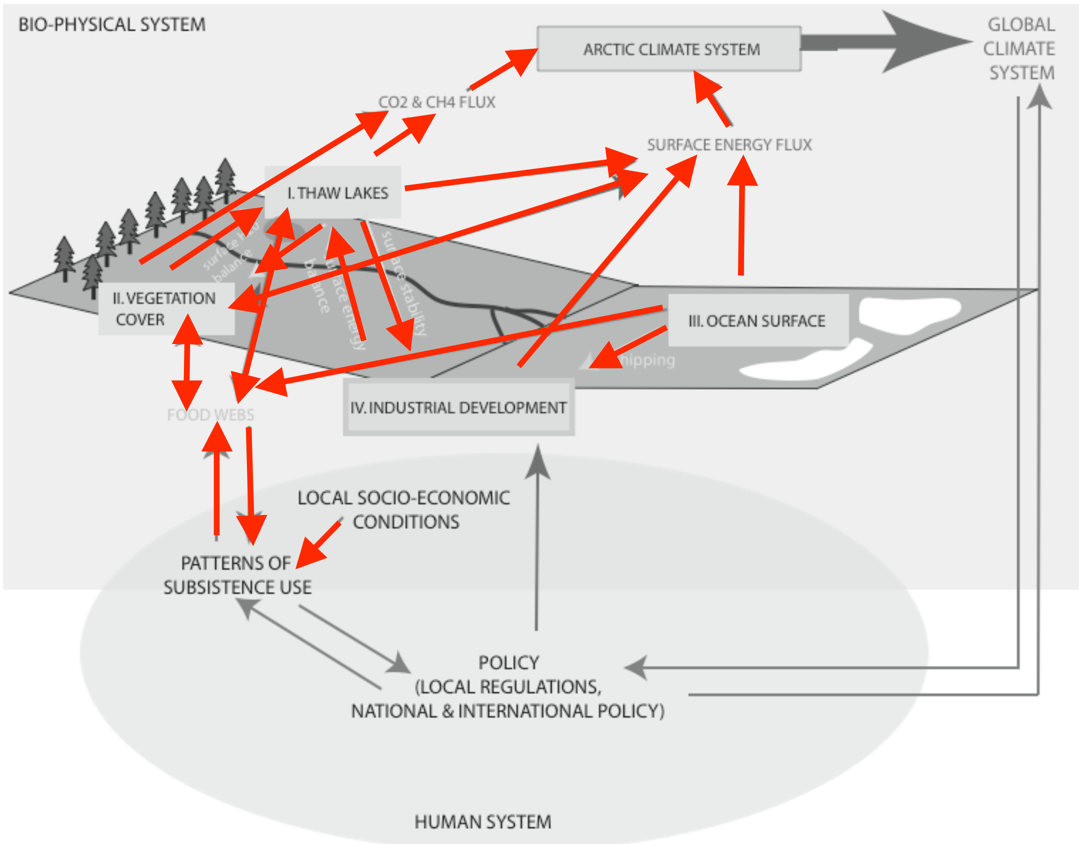

Figure 2. Schematic description of the near-surface environment. The emphasis of Phase 1 of this research program is the **linkages** among system components, as defined by transfers of energy, materials, organisms, information, etc. (see text) among components (the red arrows).

<u>Phase 2: Climate, development and near-surface change</u>

Phase 1 will provide us the necessary tools to investigate the interactions among climate and development and near surface change (Figure 3). Development in this case is broadly defined, encompassing permanent, fixed infrastructure (houses, roads, oil drilling apparatus), temporary perturbations (seismic lines), and transportation (changes in shipping). In other latitudes, land use/land cover change is considered to be a major component of global environmental change. In the Arctic, climate has been considered to be the major driver of ecosystem change thus far. However, rates of development are accelerating and may accelerate even faster as climate warms (e.g., because of improved shipping routes within the Arctic Ocean basin). Land and ocean cover change is thus likely to become an increasingly important driver of change in human systems and ecosystems in the future. Development thus acts as both a driver of change (in that development initiates profound changes in the near-surface environment) and a responder to change (in that climate warming is likely to trigger changes in patterns of development in the arctic). Furthermore, strong synergistic impacts between climate and development are likely to exist. For example, climatic influences on sea ice and terrestrial ecosystems may alter the availability of wild food sources (e.g., marine mammals, caribou, fish). At the same time, development and an expanding road network is likely to affect the availability of industrial food sources. The synergistic effects of those simultaneous changes are likely to be profound, and yet we know comparatively little on how the two drivers (climate and development) actually interact to affect food systems or any other aspect of the arctic system.

Impacts of development in the arctic are likely to be different in several important respects from impacts at lower latitudes. In the relatively sparsely populated arctic, industrial development is likely to have profound implications for patterns of human migration and habitation. Furthermore, the proportional effect of development may be very different in the Arctic than at other latitudes: urban expansion and industrial development may be occurring at a lower rate in the Arctic, but it is likely that the proportional impact of those changes may be quite a bit higher because of fragility of systems and higher necessary energy inputs. Finally, changes in infrastructure—especially the information infrastructure—may exert significant influence on human systems by changing the connectivity of remote rural villages to outlying urban areas; this may alter cultural innovation and response to environmental change. In the second phase of the near-surface research program, we particularly encourage projects that seek to understand how development and climate interactively contribute to accelerated changes and transitions in the near-surface environment.

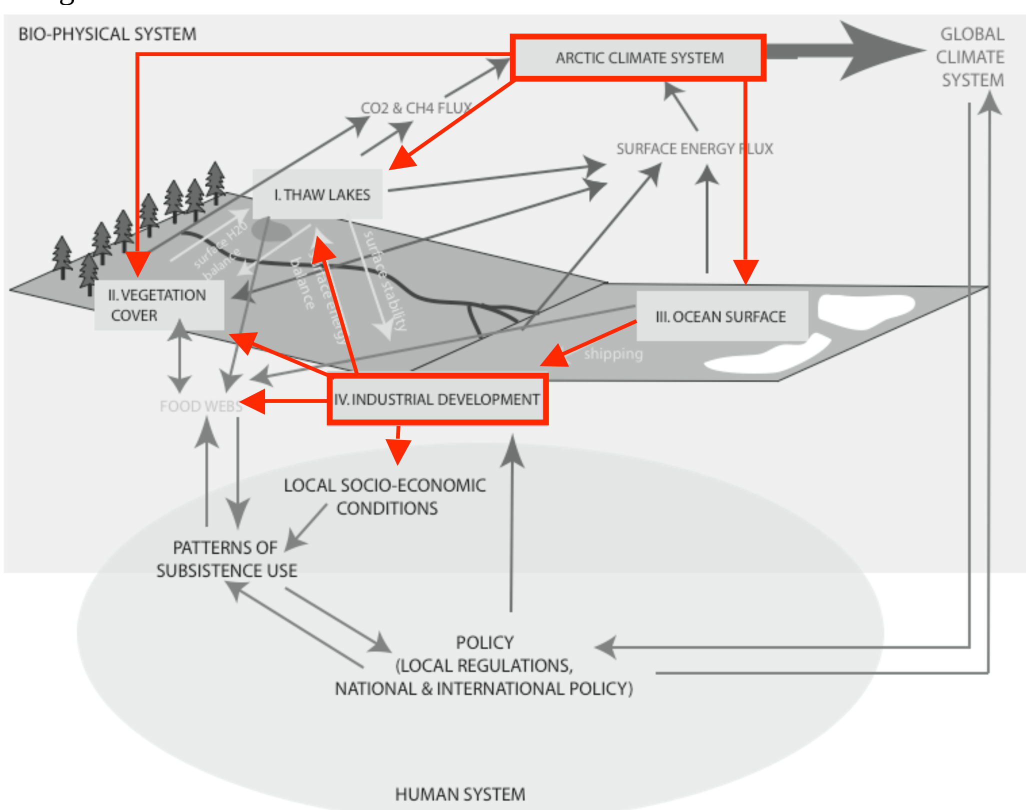

Figure 3. Emphasis in Phase 2 will shift from the internal linkages within the system to the synergistic effects of the two primary drivers of change, industrial development and climate (outlined here in red).

Phase 3: Global linkages: why arctic near-surface change matters to the rest of the world

Phases 1 and 2 will produce an improved understanding of linkages within the near-surface environment, interactions between biophysical and human systems, and the interactive effects of climate and development as drivers of near-surface change. Armed with this enhanced understanding of the Arctic System, we will be poised to answer the perennial (and frequenly neglected) question of why a changing arctic matters to the very large fraction of the human population that resides outside the arctic. In the final phase of the project, we will request proposals that explicitly investigate the linkages between Arctic near-surface change and the global earth system (red arrows and boxes in Figure 4). Although the most commonly addressed linkages between the arctic system and the global earth system are aspects of the climate system (e.g., North Atlantic deep water formation, modes of atmospheric variability), we envision a broader scope for this phase. Proposals in this final phase will, ideally, encompass a wide variety of linkages: biogeochemical fluxes and other transfers, linkages within the climate system, international policy, food systems, transportation. We envision that synthesis in this phase will produce documents geared towards guiding policy-makers within and outside the arctic.

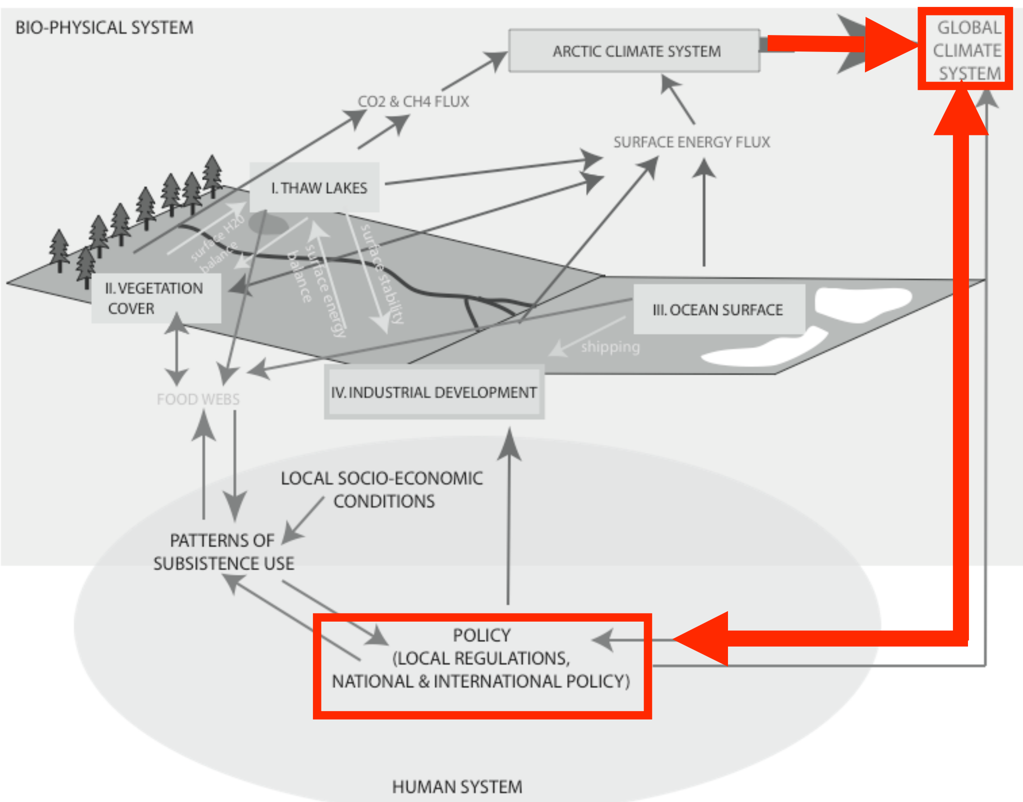

Figure 4. In the 3rd phase of the research program, the emphasis is on the importance of changes in the near-surface environment to the global earth system. In the conceptual figure, therefore, the emphasis is on the arrows that point outwards to the global climate system and national/international policy-making institutions.

Program Details

Achieving our goal and answering the questions that we have posed within this implementation plan will require integrated, synthetic, and truly interdisciplinary science. Here we propose a structure for the program that will facilitate those aspects of the science as well as contribute to the building of a community of interdisciplinary researchers and facilitate the participation of young investigators[5].

1. Mechanisms to promote integration and synthetic science:
    a. The intellectual themes outlined previously (phenology, contingencies and uncertainty, innovation and risk) will provide the integrating mechanism for each AO. For example, a research project investigating the dynamics of land-surface change (increased shrubbiness, for example) might connect with a project investigating near-shore sea ice dynamics through an exploration of phenology. How have the timing of key events changed, and how do those changes in timing mediate human (or biological) responses to the changes? *Each proposal should explicitly state how it will address at least one of the intellectual themes in the program*.
    b. Proposals must focus on "transfers"—the linkages among system components (see figures in the next section)—and must explicitly state which transfer or transfers are being studied, and why those particular transfers are important to the problem on which a particular AO focuses. *An explicit emphasis on the linkages among system components will facilitate integration by putting the research focus squarely on the transfers that occur among system components.*
    c. Although proposals need not be pan-Arctic in scope (indeed, we assume that most will not be), each proposal needs to explicitly describe its relevance to the functioning of the Arctic System[6]. *Clear relevance to the functioning of the Arctic System as a whole will further facilitate integration*.
2. Mechanisms to promote coordination and facilitate ongoing synthesis. Ongoing synthesis is essential to the success of this research program, and as such we propose that tight coordination of projects and opportunities to conduct ongoing synthesis are a necessary component of this research program. Coordinating the integration and synthesis aspects of the research program will require that funding be set aside specifically for these purposes (e.g., for annual P.I. synthesis and integration meetings); we feel that these measures are necessary to achieve the goal of an integrated, thematically based research program.[7]
    a. Successful P.I.s will attend an initial implementation meeting[8] after funding decisions are announced in order to plan integration among projects and develop conceptual linkages among projects. Proposers may allow flexibility in specific study locations and times so that these may be coordinated with other projects selected for funding. In some situations, investigators may decide that a shared geographical focus may be an important tool for integration. In others, investigators may decide that integration around the common pursuit of one or more of the problems and/or cross-cutting research themes may be more appropriate.

   b. In addition, P.I.s will attend annual all-investigator meetings for the purpose of conducting ongoing synthesis and to facilitate continued project coordination. These meetings would also, ideally, be open to post-docs or advanced graduate students and to members of communities with whom collaborations have developed. In this way, synthesis and integration will be integral to the research program and not post-hoc.
3. Mechanisms to build a community of interdisciplinary researchers. Building a community of interdisciplinary researchers is an important goal of this research program. Community-building can be encouraged through the following initiatives.
   a. Announcements of opportunity should encourage a range of project sizes, from small, single-investigator projects to large, multi-investigator projects. Although the classic model of interdisciplinary research is a large project with multiple P.I.s representing different disciplines, this model is particularly challenging for young investigators who may not have yet developed a network of contacts with which to construct an assemblage of P.I.s Single-investigator proposals that are *conceptually* interdisciplinary—that contain ideas with clear linkages to other disciplines and projects—can be integrated with other projects, and interdisciplinary connections can be forged at the initial implementation meetings that we advocated previously. Clear statements that small, single-investigator projects are encouraged—provided that those projects have the appropriate scope and intellectual connections to other projects—would facilitate community-building by opening the process more explicitly to young investigators.
   b. Young investigator proposals are particularly encouraged, in the spirit of programs like the International Polar Year's Young Investigator's Network.

Key outcomes anticipated from the STATE program

- Improved understanding of one of the most crucial aspects of arctic environmental change.
- Science that is societally relevant and designed to guide decision-making in the arctic.
- Improved understanding of interactions between human and biophysical systems.
- Improved understanding of global relevance of arctic near-surface changes.
- Community-building within the scientific community

Explanatory Notes:

[1] Although the language here may seem awkward, the key concept that we are trying to articulate is that the appropriate frame of reference in this research program is on the interconnections between system components rather than on the components themselves. A proposal that sought to understand shrub expansion, therefore, would explore that process (which is within the "vegetation cover" box) in the context of how shrub expansion alters transfers/interactions with other components. For example, expansion of shrubs alters transfers of heat between atmosphere and ground, alters transfers of moisture, and alters transfers (movements) of organisms.

[2] We broadened the zone of emphasis from 'surface' to 'near surface' in recognition that the properties of the surface are affected by processes occurring immediately below the surface (e.g., active layer dynamics) and immediately above (e.g., energy exchange with the lower atmosphere). The crucial part of this definition is that whatever investigators propose to study must be directly relevant to the land (including lakes) and ocean surface of the arctic.

[3] The single most important justification for our emphasis on the 'near-surface' environment is its importance to humans. The surface is the part of the arctic on which we live, travel, and obtain food. Relevance to human systems is a core principle of this research program.

[4] We discussed a variety of mechanisms for achieving integration—a united geographical focus, for example. We ultimately rejected the mechanisms that have been used in the past on the grounds that they would either unnecessarily restrict the scope/focus of the science or fail to achieve the desired focus on *linkages among system components*. We therefore adopted an approach of integrated based on shared intellectual themes. These themes emerged from the Near Surface Processes prospectus, and they were chosen for two reasons. First, each theme applies across domains. Phenological changes, for example, are a critical aspect of changes on land, in thaw lakes, in oceans. Second, the themes collectively describe the issues that are central to understanding how surface changes affect people.

[5] This section reflects our belief that integration and truly interdisciplinary science does not happen by accident, nor does it happen without significant investment in community-building and developing human and intellectual capital. We feel that the payoffs of successfully developing an integrated research community that crosses traditional disciplinary boundaries and integrates across the traditional domains are enormous. Achieving the goal of an integrated research community, however, requires the investment of time and funding to support integration. Although ARCSS has moved away from science steering committees, we feel strongly that an SSC in some form will be necessary to coordinate and support integrative, synthetic, community-building activities.

[6] Our goal is to understand near-surface change in the terms that are most relevant to human systems, and in many cases that will mean that the scale of the research is local rather than pan-Arctic. This is entirely appropriate for this program, *so long as the researcher can demonstrate the relevance of the project at the level of the arctic system*.

[7] This is a particularly exciting and potentially fruitful aspect of the program. The traditional model of multi-year science programs typically includes a first phase of

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intensive fieldwork and other data collection (generally multi-year) followed by a wrap-up round of synthesis at the end. We feel that synthesis should be an ongoing part of this research effort, occurring at all phases. Synthesis meetings throughout the life of the research program will make it possible to forge the intellectual linkages among projects that are necessary to create a truly integrated science community. We did not come to consensus on the specifics of the timing: some of the group felt that annual all-P.I. meetings for synthesis and integration would be appropriate, others felt that every other year meetings would be sufficient. Regardless of the specific timing, however, we all agreed that regular, face-to-face meetings were essential to the success of this project.

[8] There is precedent in previous ARCSS projects for this approach. Our idea here is that the best mechanism for integration among projects may vary depending on which projects are funded—in some years, it may be possible to enhance integration through a shared regional emphasis. In other years, projects may be geographically dispersed but integration may be possible through shared intellectual ground. Regardless, we feel that an implementation meeting occurring soon after funding decisions are made will be essential to achieving an integrated program rather than a disparate set of projects.

Near-Surface Processes Community of Practice (Co-oP)
(Surface Dynamics Co-oP and Thaw Lakes Co-oP Members Combined)

STATE Implementation Plan Writing Group in **Bold**

Lilian Alessa
Resilience and Adaptive Management Group
University of Alaska Anchorage
3211 Providence Drive
Anchorage, AK 99508
907-786-1507
afla@uaa.alaska.edu

Richard Beck
International Center For Water Resources Management (ICWRM)
Central State University
204 C.J. McLin Laboratories
Wilberforce, OH 45384
937-376-6192
rbeck@centralstate.edu

James Bockheim
Department of Soil Science
University of Wisconsin - Madison
1525 Observatory Drive
Madison, WI 53706-1299
608-263-5903
bockheim@facstaff.wisc.edu

Syndonia Bret-Harte
Institute of Arctic Biology (IAB)
University of Alaska Fairbanks
PO Box 757000
Fairbanks, AK 99775-7000
907-474-5434
ffmsb@uaf.edu

Christopher Burn
Department of Geography
Carleton University
1125 Colonel By Drive
Ottawa, ON K1S 5B6
613-520-2600 ext 3784
cburn@ccs.carleton.ca

John Cassano
Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado Boulder
University Campus Box 216
Boulder, CO 80309-0216
303-492-2221
cassano@cires.colorado.edu

Christine Cuomo
Department of Philosophy
University of Cincinnati
P.O. Box 2103274
Cincinnati, OH 45221-0374
christine.cuomo@uc.edu

Dirk Derksen
Alaska Science Center
U.S. Geological Survey (USGS)
1011 E Tudor Road, MS 701
Anchorage, AK 99503-6199
907-786-3531
dirk_derksen@usgs.gov

Claude Duguay
Department of Geography
University of Waterloo
200 University Avenue West
Waterloo, ON N2L 3G1
519-888-4567 ext 3610
crduguay@fes.uwaterloo.ca

Wendy Eisner
Department of Geography
University of Cincinnati
401 Braunstein Hall ML 131
Cincinnati, OH 45221-0131
513-556-3926
wendy.eisner@uc.edu

Eugenie Euskirchen
Institute of Arctic Biology (IAB)
University of Alaska Fairbanks
311 Irving Building I
Fairbanks, AK 99775
907-474-1958
ffese@uaf.edu

Craig Fleener
Council of Athabaskan Tribal Governments
PO Box 33
Fort Yukon, AK 99740
907-662-2587
cfleener@catg.org

Robert Frohn
Department of Geography
University of Cincinnati
401E Braunstein Hall
PO Box 210131
Cincinnati, OH 45221-0131
513-556-2849
robert.frohn@uc.edu

S. Craig Gerlach
Department of Anthropology
University of Alaska Fairbanks
PO Box 757720
Fairbanks, AK 99775-7720
907-474-6752
ffscg@uaf.edu

Kenneth Hinkel
Department of Geography
University of Cincinnati
400 F Braunstein Hall
PO Box 210131
Cincinnati, OH 45221-0131
513-556-3430
kenneth.hinkel@uc.edu

Larry Hinzman
International Arctic Research Center (IARC)
University of Alaska Fairbanks
930 Koyukuk Drive
PO Box 757340
Fairbanks, AK 99775-7340
907-474-7331
ffldh@uaf.edu

Henry Huntington
Huntington Consulting
23834 The Clearing Drive
Eagle River, AK 99577
907-696-3564
hph@alaska.net

Benjamin Jones
Alaska Science Center
U.S. Geological Survey (USGS)
4230 University Drive, Suite 201
Anchorage, AK 99508-4650
907-786-7033
bjones@usgs.gov

Steve Kokelj
Renewable Resources and Environment
Water Resources Division
Indian and Northern Affairs Canada
PO Box 1500
Yellowknife, NT X1A 2R3
867-669-2656
kokeljsv@inac.gc.ca

Scott Lamoureux
Department of Geography
Queen’s University
Mackintosh Corry Hall
Room D126
Kingston, ON K7L 3N6
613-533-6033
lamoureu@post.queensu.ca

Andrea Lloyd
Department of Biology
Middlebury College
Bicentennial Hall 372
Middlebury, VT 05753
802-443-3165
lloyd@middlebury.edu

Glen MacDonald
Departments of Geography and
Ecology and Evolutionary Biology
University of California Los Angeles
405 Hilgard Avenue
Los Angeles, CA 90095-1524
310-825-2568
macdonal@geog.ucla.edu

Carl Markon
Alaska Geographic Science Office
U.S. Geological Survey (USGS)
4230 University Drive Suite 230
Anchorage, AK 99508-4664
907-786-7023
markon@vector.wr.usgs.gov

Eric Maurer
Center for Environmental Studies
University of Cincinnati
614 Rieveschl Hall
Cincinnati, OH 45221-0006
513-556-9706
eric.maurer@uc.edu

Joe McFadden
Department of Ecology, Evolution, and Behavior
University of Minnesota
100 Ecology Building
1987 Upper Buford Circle
St. Paul, MN 55108
612-624-7238
mcfadden@umn.edu

Martin Miles
Environmental Systems Analysis Research Center (ESARC)
4450 Arapahoe Avenue, Suite 100
Boulder, CO 80303
303-415-2515
martin.miles@esarc-colorado.org

Jeffrey Munroe
Department of Geology
Middlebury College
Bicentennial Hall 414
Middlebury, VT 05753
802-443-3446
jmunroe@middlebury.edu

Maribeth Murray
Department of Anthropology
University of Alaska Fairbanks
PO Box 757720
Fairbanks, AK 99775-7720
907-474-6751
ffmsm@uaf.edu

Frederick Nelson
Department of Geography
University of Delaware
216 Pearson Hall
Newark, DE 19716
302-831-0852
fnelson@udel.edu

Craig Nicolson
Department of Natural Resources Conservation
University of Massachusetts
160 Holdsworth Way
Amherst, MA 01003-4210
413-545-3154
craign@forwild.umass.edu

Nicolai Panikov
Department of Chemistry and Chemical Biology
Stevens Institute of Technology
Castle Point on Hudson
Hoboken, NJ 07030
201-216-8193
npanikov@stevens.edu

Kim Peterson
Department of Biological Sciences
University of Alaska Anchorage
3211 Providence Drive
Anchorage, AK 99508-8104
907-786-4772
afkmp@uaa.alaska.edu

Joshua Schimel
Department of Ecology, Evolution, and Marine Biology
University of California Santa Barbara
507 Mesa Road
Santa Barbara, CA 93106
805-893-7688
Schimel@lifesci.ucsb.edu

Gaius Shaver
The Ecosystems Center
Marine Biological Laboratory
7 Water Street
Woods Hole, MA 02543
508-289-7492
gshaver@mbl.edu

Laurence Smith
Department of Geography
University of California Los Angeles
PO Box 951524
1255 Bunche Hall
Los Angeles, CA 90095-1524
310-825-3154
lsmith@geog.ucla.edu

Michael Steele
Polar Science Center Applied Physics Lab
University of Washington
1013 NE 40th Street
Box 355640 Henderson Hall
Seattle, WA 98105-6698
206-543-6586
mas@apl.washington.edu

Heidi Steltzer
Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, CO 80523-1499
970-491-5724
steltzer@lamar.colostate.edu

Matthew Sturm
Cold Regions Research and Engineering
Laboratory - Alaska
PO Box 35170
Ft. Wainwright, AK 99703-0170
907-353-5183
msturm@crrel.usace.army.mil

Craig Tweedie
Department of Biology and
Environmental Science and Engineering
Program
The University of Texas at El Paso
500 West University Avenue
Biology Building Room 226
El Paso, TX 79968-0513
915-747-8448
ctweedie@utep.edu

Donald (Skip) Walker
Institute of Arctic Biology (IAB)
University of Alaska Fairbanks
262 Arctic Health Building
PO Box 757000
Fairbanks, AK 99775-7000
907-474-2460
ffdaw@uaf.edu

Jeffrey Welker
Environment and Natural Resources Institute
University of Alaska Anchorage
707 A Street
Anchorage, AK 99501
907-257-2701
afjmw1@uaa.alaska.edu

Daniel White
Institute of Northern Engineering
University of Alaska Fairbanks
248 Duckering Building
PO Box 755900
Fairbanks, AK 99775-5900
907-474-6222
ffdmw@uaf.edu

Tingjun Zhang
National Snow and Ice Data Center
Cooperative Institute for Research in
Environmental Sciences
University of Colorado
Campus Box 449
Boulder, CO 80303-0449
303-492-5236
tzhang@nsidc.org

Surface Transformations in the Arctic Environment (STATE)
A Prospectus of Science Priorities
from the Near-Surface Processes Community of Practice

Recent decades have transformed the combined land and sea surfaces across the Arctic. Marine areas that were formerly covered by sea ice are now open water in summer, significantly altering albedo, surface temperature, and atmospheric moisture. In the terrestrial realm, thaw lake dynamics have changed significantly throughout Alaska, Canada and Siberia as near-surface permafrost thaws. Tall shrubs and trees are replacing low tundra vegetation throughout the low Arctic, initiating feedbacks on surface energy exchange that will ultimately result in enhanced surface warming. An increasing proportion of the land surface is also being transformed by industrial development, with associated infrastructure such as pipelines, roads and mines fragmenting habitats, affecting ecosystem dynamics and surface hydrology, and in some places significantly changing the number and distribution of wild game. Federal, state and provincial agencies in Alaska and Canada are not effectively responding to rapid and widespread changes in seasonality associated with global climate change, with serious effects on both subsistence harvest success and access to traditional harvest areas, and on the nature and pace of industrial development.

These changes are both a visible manifestation and potential driver of ongoing global change across a range of spatial and temporal scales. Many of the impacts of ongoing climate change on humans – both in and out of the Arctic –are now being and will continue to be mediated by these changes in the near-surface environment. Despite their importance, the collective impacts and relative importance of different drivers of change remain poorly understood. *The central goal of the Near-Surface Processes Co-OP is to understand the cumulative and interactive effects of near-surface terrestrial and marine environmental transformations on the future state of the Arctic System.*

Overview of the Near-Surface Processes Co-OP

Our Community of Practice is an integrated group of natural, social, and physical scientists (see Appendix for current participants) organized around three fundamental questions related to earth surface change in the Arctic.

(1) What are the rates and trajectories of spatial and temporal changes in the near-surface environment on land and in the ocean?

(2) What are the relative roles of, and interactions among, climate and human activities in driving changes in the near-surface environment on land and in the ocean, and what are the most important linkages at different scales?

(3) How will cumulative changes and their resultant feedbacks affect human societies and their use of Arctic resources? How might changes in the land and ocean surface, individually and collectively, interact with other forces of global change to affect human populations and resource use in the Arctic? While there has been considerable research about global climate change, there has not been enough research funded or carried out on the "downscale" effects of global change on human communities at regional and local levels (e.g., Millennium Ecosystem

Assessment, 2005[1]). With respect to specific impacts on human communities, a driver of change at one spatial or temporal scale may be better understood as a combination of feedbacks and interactions at another

We propose several avenues to achieve these goals, including integration and re-analysis of existing data, coupled regional and global modeling efforts, and integrated field research projects aimed at filling data gaps and furthering our understanding of the causes, consequences, and linkages among land and ocean surface change in the circumpolar Arctic. There is a particular need for historical work using multiple proxies to extend the temporal frame of reference with respect to terrestrial, human, and marine components of the Arctic system. The priority in research should be on projects that specifically investigate linkages among components (rather than isolated 'case study' projects) and on projects that address crucial gaps (geographical or otherwise) in our understanding of the components of the near-surface environment. Projects advancing the goals of this Co-OP should seek to understand near-surface change at broad spatial and temporal scales, with clear plans to integrate across multiple scales. We emphasize that achieving a broad-scale understanding of surface change will require research at a range of spatial scales, from plot-level science to efforts that span the circum-arctic. Regardless of the primary scale at which the research occurs, however, integration across temporal and spatial scales, as well as integration among domains, must be an explicit outcome of the research. As such there is a critical need for both in-situ and remote sensing observational efforts and regional and global modeling.

The science priorities described in this document build on past ARCSS-related research. However, our Co-OP has defined an approach that will push future Arctic System science in novel and productive directions, as follows:

1. **Transition zones paradigm**. Whereas prior ARCSS research efforts, such as LAII and OAII, emphasized the interactions between the various 'domains' of the Arctic system (e.g., land and atmosphere, land and cryosphere), we suggest that the Arctic System can also be understood as a set of interfaces, or transition zones, between domains. We are proposing a coordinated research effort aimed at understanding the near-surface environment, as the interface between sub-surface permafrost and land/ocean and atmosphere. We define the near-surface transition zone loosely as follows: on land it extends from deep within the permafrost up to the tropopause, and on ocean from depths of 200-500 m to the tropopause. Each of our four research priorities, listed below, represents a crucial aspect of the near-surface transition zone. This emphasis on transition zones (or interfaces) rather than traditional approaches focused on domains themselves allows us to investigate the part of the Arctic System that is undergoing the most visible and rapid change, while avoiding the simplifying assumptions that are an inherent part of 'domain-centered' research efforts. The transition zone paradigm emphasizes again that it is the *linkages* among domains that are of interest, rather than (or at least in addition to) the domains themselves.

2. **Physical–human dimensions**. Physical and social scientists, along with researchers from the humanities, are working together toward the goal of

[1] Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Island Press.

understanding the critical components of Arctic System change that have the potential to acutely and chronically affect human societies. These efforts are supplemented and enhanced by including indigenous knowledge holders as collaborators because this group has both a unique understanding of local processes, and is most directly impacted by change. There is a particular need, at this point in time, for research on rapid and short-term change, as change is now occurring at a rate faster than people and institutions/regulations can respond. Collaboration with local stakeholders should have, as an explicit outcome, the building of local and regional capacity for rapid individual and collective responses to change. The cross-cutting focus of our Co-OP on both human and non-human dimensions of near-surface change is an important advance from the disciplinary based structure of the 'old ARCSS, and is different from the way that social science research is currently structured at.

3. **Humans as drivers and responders**. The conceptual framework views humans as both drivers of and responders to change in the Arctic. Within this framework, human activities and infrastructure (and the policies that guide use and development) are incorporated as both drivers of and responses to change in continuous feedback loops operating at various spatiotemporal scales.

Near-surface change on the land and ocean is the focus and purpose of this document. The science priorities described here are not designed to provide an-inclusive or comprehensive list of variables, processes or questions reflect understanding of the Arctic system as a whole. We confine our efforts here to near-surface transition zones, as described in detail below, with emphasis on regional and local scales of temporal and spatial integration and differential impacts of the same on arctic human. At the close of this document we outline a prospectus for connections that must be developed with other research groups in order to embed this effort in broader and ongoing research that address other aspects of Arctic System change.

Research Priorities for Understanding Near-Surface Change

We focus on four critical components of near-surface change in the Arctic: changes in the ***dynamics of thaw lake*** formation, expansion, and drainage; changes in ***vegetation cover***; changes in the ***ice/ocean surface***; and the direct, indirect and cumulative impact of ***industrial development*** and exploration (with particular emphasis on the synergistic effects of industrial development in the context of a changing climate). Each component illustrates significant recent change, has potential for continued rapid change, has strong feedbacks to the climate system, and has major impacts on human populations through multiple dimensions of the coupled social-ecological system. A central component of our research is the coupling of the bio-physical and human elements of the Arctic system. In Figure 1, the bio-physical variables and sub-systems are highlighted by the light blue rectangle; human social and economic sub-systems are highlighted by the pale yellow oval. Human interactions with the bio-physical sub-systems primarily take the form of subsistence activities (which both affect and respond to ecosystem food web dynamics) and industrial development (including preliminary phases of development, such as exploration, which may have little direct effect on the surface, but may have potentially large effects on species such as caribou and waterfowl).

These components of the arctic system are linked with the global system through two primary mechanisms: (1) arctic surface change has strong feedbacks on the arctic climate system, as illustrated by the red arrows linking the four components of change with the arctic climate system. These feedbacks are primarily caused by changes in surface energy exchange and greenhouse gas fluxes; (2) changes in the global climate system are hypothesized to affect local, national, and international policies governing industrial development in the Arctic. These multiscaled and multileveled institutional frameworks govern the individual and collective response to climate change; although there is substantial theory in this area, there is little substantive research on the regional level about how stability and change in the institutional domain mediates local and regional responses to climate.

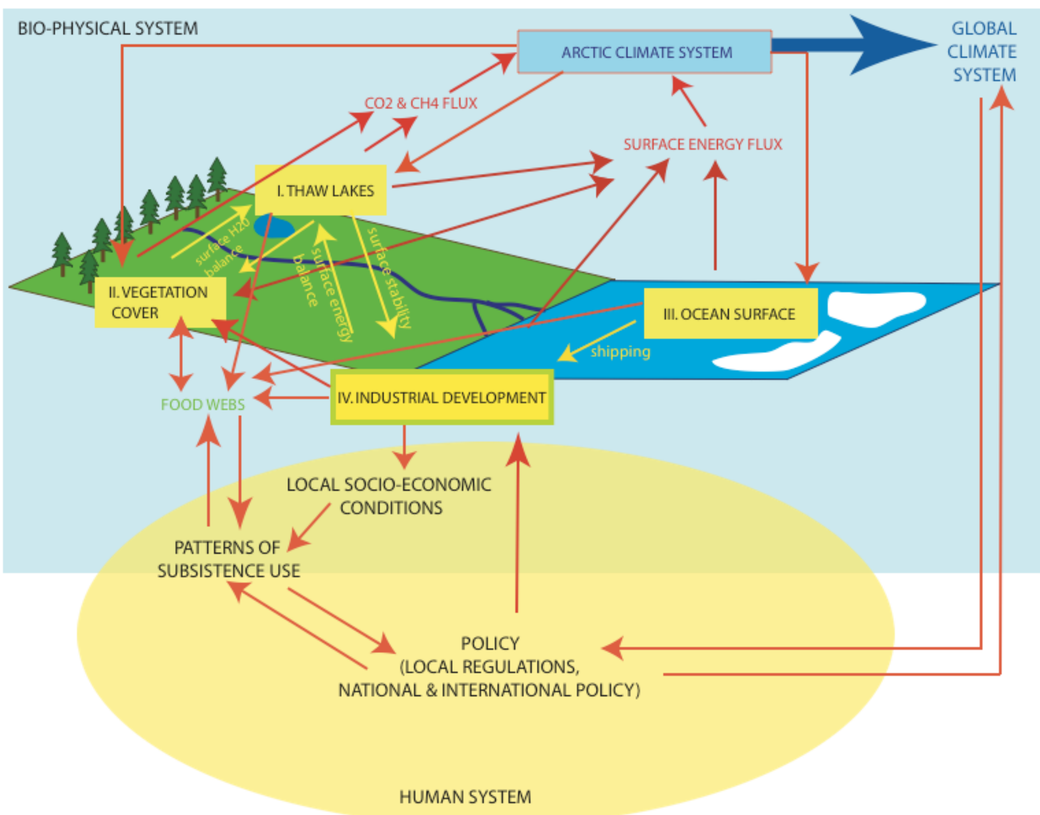

Figure 1. Components of the Arctic System addressed by the Surface Dynamics Co-OP

I. The Thaw Lake cycle

Thaw lakes cover about 20% of the continuous permafrost zone of northern Alaska, as well as a substantial part of the Canadian and Eurasian Arctic. This provides an excellent model system in which to explore the interfaces between permafrost, the water cycle, vegetation, and atmospheric processes. The basins that develop when lakes eventually drain constitute an additional 26% of the terrestrial surface. Lakes are therefore the primary geomorphic component of the landscape, and lake processes are the dominant geomorphic agent of change. Thaw lakes represent the effects of permafrost thermokarst at the surface, and respond to regional or global climate forcing. Lakes, in turn, alter the thermal regime of the underlying permafrost. Drained thaw lake basins are sites for preferential accumulation of soil organic carbon that could mobilize given regional warming. Larger lakes and lake basins provide habitat for fish and wildlife, and are important natural resources for indigenous people, municipalities and industry. In addition to being the location of some of the most active C, water, and nutrient stocks and cycles, thaw lakes represent an excellent model system for investigating changes in surface properties at relevant temporal and spatial scales for ARCSS. Central themes to be addressed by the Near-Surface Dynamics CO-OP include:

1. What are the formative and dynamic thaw lake processes, and how do they vary over time and space?
2. What are the important feedback cycles and fluxes between lakes and permafrost, vegetation, the atmosphere, and the global biogeochemical cycle?
3. How are thaw lake used by humans, and how can this resource be sustained given the growing pressure from local communities and industry in the face of climate-driven change?

Table 1. Key processes and questions relevant to understanding changing thaw lake dynamics.

Process	**Description and rationale**
Thaw lake initiation	Does the thaw-lake cycle exist in northern Alaska, and what is the duration? Generally, how long have thaw–lake processes been operating? Specifically, at what rate do lakes expand, what are the primary drainage mechanisms, and what are the spatiotemporal patterns? How has past climate and geomorphic change (last ~20,000 years??) affected the development, extent, and eventual drainage of thaw lakes across diverse arctic landscape types? How is carbon sequestration and peat accumulation within the drained thaw lake basins related to past climatic changes? We are seeing changes in thaw lakes throughout Alaska and in Siberia, but they appear to have different driving mechanisms in different regions. What are the factors controlling recent thaw lake changes?
Lake physical processes (erosion, thermokarst, orientation)	Have erosion and sedimentation patterns in thaw lakes changed appreciably since the benchmark studies of the mid-1960s? If so, do they support current models for thaw lake genesis, the thaw lake cycle and climate change? How do thaw-lake orientation and morphometry vary over space and time, and do sharp gradients exist? Are the orientation and morphometric characteristics of thaw lakes invariant over a broad range of scale or do they involve geomorphic thresholds? What factors influence the 3-d lake morphometry (shape, size, orientation, depth)? How can climatic influences be separated from the effects of local factors? What are the proximate causes of regional differences in thaw lakes including size distribution, shape, and dynamics?
Lake response to environmental change	How will the abundance and distribution of present-day lakes and wetlands change in response to continued Arctic warming? Does the rate of thaw lake expansion and/or contraction, drainage, and size frequency distribution change as a consequence of climate change, and can thaw lake statistics be used as an integrative measure of climatic trends? Can remotely sensed data provide proxy information for current and recent thaw lake erosion and sedimentation patterns given adequate ground truth? How do changes in lakes translate or relate to changes in the surrounding areas and conditions? Do shrinking lakes accompany drying of adjacent soils, succession of dominant vegetation species, and wider scale degradation of permafrost? And if so, to what extent (both spatially and in terms of percent change of the variable in question) do these changes relate to the lakes' rate of change.

Lake biological processes	What is known about communities in thaw lakes (microbes, algae, macrophytes, fauna) and is there difference (species diversity, abundance, functional groups) between lakes and tundra soils and between lakes and underlying permafrost? Are the current dynamics of thaw lakes formation influenced (catalyzed, accelerated) by microbial processes in permafrost? How significant is methanogenesis and biological heat generation in the lake thaw bulb? Is there stimulation of microbial activity at the 'permafrost-water' interface? What particular biogeochemical processes contribute to the currently observed changes in thaw lake geometry? What are the relationships between changes in climate and the surrounding tundra and extant aquatic communities, and what data are required to predict the response of thaw lakes and their biotic communities to climate changes? How do factors such as thaw lake morphometry, orientation, surrounding soil & vegetation characteristics and the spatiotemporal dynamics of lake drainage, expansion & contraction influence the biota and the trophic structure of lakes?
Lake-permafrost interactions	What is the response of ground thermal regime (talik formation/freeze-up, active layer and permafrost temperatures) under thaw lakes & basins to climate changes in the Arctic; what is the nature of the lake/basin and atmosphere interaction? What is the ground thermal status under lakes & basins at various stages of the thaw lake cycle, especially over the centennial to millennial scale?
Energy, water, and nutrient fluxes	What is the role of thaw-lakes in the energy and water cycling of lake-rich regions of the Arctic? What are the impacts of large-scale teleconnections on the water balance of thaw lakes? What are the fluxes of heat, water and nutrients as well as the C-fluxes through the following boundaries: (a) underlying permafrost & lake water (vertical mass- energy transfer); (b) adjacent permafrost & lake water (horizontal transfer); (c) lake & atmosphere?
Temporal changes in fluxes	What plant and soil processes control vegetation succession after the drying of thaw lakes, and what are the biogeochemical feedback consequences at short and long time scales? What are the biogeochemical consequences of the thaw lake cycle, and especially on carbon currently sequestered?
Spatiotemporal variation	How do successional processes in thaw lakes of Alaska differ from those throughout the Arctic? Do the more rapid dynamics of the thaw lake cycle influence the degree of synchrony in lake characteristics (biotic, physical & chemical); is there a greater degree of synchrony among lakes in thaw lake regions than in more temperate regions where the dynamics of lake changes/evolution differ?
Lake-human interactions	What are the uses that humans make of thaw lakes? How have these uses persisted or altered over time? To what extent are any such changes due to changes in the lakes themselves, as opposed to societal changes in the community using the lakes? How have changes in the thaw lake cycle affected wildlife and substistence resources? What impacts has industrial development had on thaw lake cycles (e.g., Teshekpuk Lake)?
Lakes as resources	What characteristics make specific thaw lakes especially suitable for various human uses such as fishing, drinking water, and bird hunting? Are these characteristics related in any way to the stage or age of the lake (e.g., how long does it take to establish a viable fish population)? What relationships to other subsistence resources besides fish? How do lakes function as a 'resource patch' for a number of ecosystem services/resources used by humans?
Indigenous Knowledge	How can IK be included in this research to promote mutually beneficial relationships that improve our understanding of landscape changes in general and thaw-lake processes in particular? How can we incorporate IK of biotic communities in thaw lakes and streams, and compare these observations to data collected in the region? Do indigenous people manage resource extraction rates (fish, waterfowl, etc.) and, if so, how? How is local knowledge of thaw lakes changing in response to rapid climatic/biophysical changes? What innovations

	are occurring to allow people to adapt to rapid change?

II. Vegetation cover

The Arctic tundra biome, which dominates the Arctic terrestrial surface, can be thought of as continuous, narrow ecotone between forested vegetation to the south (in the southern Arctic and subarctic) and the Arctic Ocean to the north. The vegetation that makes up this biome can be understood, in our paradigm of exploring interfaces or transition zones, as the interface between land surface and atmosphere. Changes in physical variables such as temperature and precipitation have already led to significant alterations of this biome, with forest vegetation expanding from the south, tall woody tundra vegetation expanding throughout the low Arctic, and productivity and abundance of key functional groups such as lichen, mosses, and sedges changing at the northern edge of this gradient. Taller vegetation more effectively traps snow, with consequent thermal impact on the underlying permafrost. These changes in the cover of the land surface are one of the most visible manifestations of climate change in the Arctic, and have significant consequences for energy budgets, biodiversity, human use of arctic resources, and global feedbacks. A complete documentation of the spatial and temporal patterns of change in the Arctic land surface is an important goal, and, indeed, patterns of change are already being investigated in a number of existing projects (see Linkages section below). The Near-Surface Dynamics Community of Practice is focused on investigating several questions with respect to land cover change.

1. What are the driving mechanisms of vegetation change, and how do they vary over time and space?
2. What are the temporal trajectories and spatial patterns of future change?
3. What are the consequences of change for human societies and upper trophic levels within food webs?
4. How does vegetation change impact the stability of permafrost and thermokarst?

The key processes and variables necessary to address these questions are summarized in Table 2.

Table 2. Key processes and variables relevant to understanding change in vegetation cover.

Process or variable	**Description and rationale**
Ecosystem/community structure	Vegetation change has been documented through the tundra biome, with widespread changes occurring in abundance of key functional groups (shrubs, moss, lichen, sedges). Further documentation of temporal changes in community structure, with special emphasis on spatial heterogeneity in the trajectories of change, is needed.
Food web structure	It is assumed that changes in vegetation—increased shrubbiness, for example—will have large effects on higher trophic levels, as amounts of preferred forage species increase and decrease. Changes in secondary metabolites may also occur as a result of climate change, and this, too, will affect the dynamics of foraging herbivores. Changes in food web structure may feedback on vegetation (for example, decreased herbivory may lead to increases in the abundance of preferred species). Changes in food web structure are also a key mechanism by which vegetation change affects Arctic residents. Exploration of the consequences of ongoing vegetation change for higher trophic levels is thus a key goal of this community.

Industrial development	Expansion of industrial development—roads, buildings, mines—has direct effects on vegetation, caused by clearing of land and removal of biomass. Industrial development also has important indirect effects on vegetation via its influence on surface energy flux, permafrost, and water balance. Industrial development in the form of roads may also provide an avenue for the invasion of exotic species into the Arctic.
Surface energy flux	Surface energy flux is one of the key processes by which changes in vegetation can feedback on the climate system. Further understanding of the effects of changes in plant functional types on surface energy flux is needed, particularly in those zones and locations that have not been well studied thus far.
Evapotranspiration and surface water balance	Changes in dominant vegetation are likely to be highly sensitive to changes in surface water balance, and to have a large effect on evapotranspiration. Understanding the role of surface water balance as both a driver of ecosystem change (e.g., effects of changes in thaw lake cycle on terrestrial vegetation) and a responder to ecosystem change (e.g., effects of increased shrubbiness on surface hydrology) is an important goal of this community.
Snow cover and duration	Snow cover has a profound influence on vegetation, primarily by modifying the severity of the winter environment and moderating soil temperature. Vegetation, in turn, has a profound influence on snow cover: taller vegetation generally traps snow. Previous research has identified important linkages among snow cover, energy feedbacks, vegetation, and soil nutrients.
Soil C and nutrient pools and cycles	Changes in vegetation – particularly those that involve shifts in the abundance of woody plants and peat-forming mosses—are linked to changes in C/nutrient cycling. Feedbacks between vegetation change and nutrient cycling have already been identified for some aspects of vegetation change (e.g., increased shrubbiness), and undoubtedly exist for many more. Studies of how warming will affect belowground thermal and biochemical processes, and how those processes will interact with vegetation change, are needed to assess the trajectory of net ecosystem C flux in the next several decades.

III. Ice/ocean surface

Changes on and near the ocean surface have paralleled changes in land cover and, like the vegetation on land, the ocean surface (with or without ice cover) is the interface between the marine environment and the atmosphere. As with land-cover change, changes on and near the ice/ocean surface are both a visible manifestation of warming and a key avenue by which warming will affect human activity in the Arctic. (Indeed, marine transportation has already been affected by sea ice changes, as has access to marine food and other resources.) Broad declines in sea ice extent and thickness, warmer sea temperatures, and changes in ocean circulation have been well documented in recent years, and are the subject of a number of ongoing efforts (e.g., SEARCH, NOAA's State of the Arctic initiative), which we will leverage rather than duplicate. The ice/ocean research developed from the Near-Surface Dynamics Co-OP will emphasize understanding transition zones, interactions and coupled physical–human dimensions. It is anticipated that regional-scale studies will be focused predominantly on circumarctic marginal seas, in relative proximity to land. We suggest that our overall goal of understanding collective near-surface change in the Arctic requires addressing the following questions.

1. What are the spatiotemporal patterns and future trajectories of change in sea ice cover and thickness, in near-surface ocean properties, and in processes that control air–sea exchange such as near-surface winds and wave height?

2. What are the implications of these changes biogeophysically (e.g., for upper trophic levels and on the stability of subsea permafrost and gas hydrates) and for humans?

Table 3. Key variables within the "ice/ocean surface" domain most relevant to understanding near-surface change in the Arctic.

Process or variable	**Description and rationale**
Sea ice cover	Like vegetation on land, sea ice is the 'keystone' physical variable that shapes the ocean surface and the near-surface transition zone. The dynamics (temporal and spatial) of changing sea ice cover are crucial for predicting the trajectory of change in the arctic climate system, the trajectory of change in marine food webs, as well as impacts on subsistence and industrial-scale human use of the marine environment. Key aspects are e.g., degree, duration and timing of ice-free conditions north of Alaska and in other marginal seas.
Sea ice thickness	Sea ice thickness is a crucial determinant of factors like ocean heat exchange and ease of transportation across and/or through sea ice. Changes in the multi-year ice area may be as important sea-ice thickness per se for near-surface change.
Sea surface temperature Wind and wave state	We include these two variables as key components of the ocean surface domain for the simple reason that as sea ice cover and thickness declines, these variables will be increasingly relevant descriptors of the state of the Arctic Ocean. Sea surface temperature and near-surface winds are crucial factors in heat, moisture, and gas exchange between the Arctic Ocean and the atmosphere. Wave state has critical human dimensions implications- there is already evidence (at least anecdotally) that increased wave height along the Arctic coast is inhibiting transportation in small watercraft.

IV. Industrial development

Industrial-scale development in the Arctic is likely to be strongly affected by changes in land and sea ice covers; industrial-scale development is also likely to be an increasingly important driver of change in land cover in the Arctic. Although much of the Arctic remains *relatively* unaffected by industrial development, the GLOBIO project[2] found that large areas of the Arctic are already within the "impact zone" of human settlements and infrastructure. Much of our focus in this section is on the *impacts* of land cover and sea ice change on human activity, but we also feel it is crucial to consider how the role of humans as direct *drivers* of change in the Arctic may alter over time through myriad feedbacks. As the Arctic becomes more accessible, this trend is likely to continue and direct human activity may become an increasingly important driver of land cover change at various spatial scales. Achieving our overall research goal requires addressing three key questions.

1. How are changes in land cover and sea ice cover likely to affect resource use at multiple scales in the Arctic?
2. How are changes in land cover and sea ice cover likely to affect possible trajectories of industrial development, natural hazards, and infrastructure stability in the Arctic?
3. What are the relative contributions of human activities in driving changes in land cover, both currently and under future change scenarios?

[2] http://www.globio.info/region/polar/

Answering these questions will require investigation of the variables and processes summarized in Table 4.

Table 4. Key processes and variables relevant to understand changing patterns of industrial development.

Process or Variable	Description and Rationale
Sociopolitical and geopolitical responses	The Arctic has been a venue for change over millennia but increasingly rapid rates of change challenge social and geopolitical systems which exhibit qualities of both remoteness and modernity. Social responses to change, including policy and decision-making at regional levels, may significantly influence the ways in which cultures adapt and evolve. Functional degradation of land and ocean networks can result in both acute (catastrophic) and cumulative (gradual) changes in human societies and their policies. These, in turn, affect other biotic and abiotic systems on different spatial and temporal scales and can result in both opportunity and risk. Thresholds at which social systems become incapable of adapting to change comprise areas of inquiry that will fill a much-needed gap in estimating and managing future scenarios. Sociocultural responses are poorly understood yet critical to our understanding of how the Arctic system will behave as a system
Transportation, industrial development and infrastructure	Transportation on the land surface is likely to exhibit a highly non-linear response to warming. If permafrost thawing eventually leads to differential ground subsidence and thermokarst, transportation may become more costly as existing infrastructure area destabilized. As transportation changes, rates of industrial development are likely to increase, both on land and in offshore areas. (Oil and gas development in offshore areas of the Barents Sea, for example, has already begun and is expected to accelerate dramatically within the next decade.) Development is becoming a contentious issue in many parts of the rural arctic where development was previously not considered because of high costs. Reduction in sea ice thickness and extent may open the Arctic Ocean to shipping, while reducing the suitability of the ocean surface for travel and subsistence activities by Arctic residents. Increased shipping along the ocean surface may have minimal impacts on the ocean itself, but the effects of changes in shipping concurrently with industrial development are unknown. Transportation may function as a linking variable under some climate scenarios. The GLOBIO project identified that significant areas of the Arctic, particularly in Eurasia, are already well within the impact zone of human development (defined as the area in which biological processes are affected by human activity and infrastructure). The vision of the Arctic as a pristine landscape free of industrial development is unsupported by existing data, and industrial development has the potential to act as a significant driver of change in coming years.
Harvest/use of biological resources	Simultaneous changes in land cover and sea ice are likely to have significant impacts on upper trophic levels and thus disrupt the harvest and use (e.g., reindeer herding) of animal populations for both subsistence and commercial reasons. Furthermore, the simultaneous nature of food web disruption on land and at sea may lead to non-linear interactions. For example, disruption of land-based food resources might lead to more pressure on ocean-based food resources (or vice versa). Changes in either terrestrial or marine-based development activity may also affect hunting and fishing pressure in coastal areas. Expanding thaw lakes or increased thermokarst may increase waterfowl habitat while simultaneously reducing

	caribou grazing area.
Food systems analysis	In addition to exploring the effects of climate change on subsistence activities, analysis is needed of what people actually eat, and how food systems will respond to changes in seasonality, access to resources, etc. How dependent are rural communities on connections to urban communities? How is access to food resources constrained by political and institutional frameworks and by industrial development? What are the vulnerabilities of rural food systems?

Coupling of bio-physical and human socio-economic systems

The four previously described aspects of changes in the near-surface environment interact with diverse patterns of human activity in the Arctic. Depending on the spatial and temporal scales of study, effects can range from changes in subsistence resource use to trans-national development of remote resources (e.g., mining and energy development). Local and regional patterns of use have already been affected by surface transformation. Coastal residents report changes in access to marine food resources, for example, in conjunction with changing sea ice patterns. Changes in coastal weather that accompany loss of landfast ice have affected the ability of indigenous people to use small boats to travel and hunt.

We propose that human interactions with near-surface changes can be understood in the context of two connected feedback loops. The first of these loops is anchored in effects of the near-surface environment on marine and terrestrial food webs and hence the abundance of key prey species (marine mammals, fish, caribou, waterfowl; Figure 1). Patterns of subsistence use of these resources can be affected by near-surface change through two mechanisms. First, direct effects of changes in the near-surface environment can influence patterns of resource use. Expanding thaw lakes and increased thermokarst may increase the available habitat for migrating waterfowl, leading to an increase in use of that food resource. Similarly, industrial development may alter the abundance and/or movement patterns of some key species. Inupiat hunters report that seismic exploration *preceding* oilfield development in NPRA is influencing movement patterns and abundance of species such as caribou, deflecting bowhead migration routes by as much as 12 miles. When coupled with changes in landfast and other aspects of sea ice, these changes are disastrous for subsistence activities. Second, changes in local socio-economic conditions that coincide with industrial development may alter patterns of subsistence use (decreasing, for example, reliance on traditional food sources). A comprehensive analysis of the effects of near-surface environmental change on subsistence resource use needs, therefore, to consider the synergistic effects of simultaneous changes in the various components of the near-surface environment. Furthermore, humans need to be considered as both a responder to change (e.g., altering patterns of resource use as prey species fluctuate in abundance) and as a driver of change. Subsistence resource use, for example, may affect prey species abundance. It is also plausible that concern over the effects of development on prey species and other resources could affect policy and thus feedback on industrial development. We feel that it is essential that research into human interactions with near-surface change recognize that humans are both drivers and responders.

The second feedback loop defining human interactions with the near-surface environment is anchored in the policy realm, and involves industrial development that is often initiated by, and frequently has large effects on, non-Arctic residents. Policy-making institutions at the local, regional, national, and international scales are the ultimate driver of industrial development in the Arctic and are *also* drivers (to some extent) of the global climate system. Understanding the interactions between policy-making institutions and local dynamics within the Arctic is an important goal of this research.

Coupling of near-surface change to the global climate system

A final element of our research priorities is to define the relevance of changes in the near-surface environment in the Arctic to the world beyond the Arctic. The effects of changes on thaw lake dynamics, for example, to Arctic residents is clear. But what is the relevance of these changes to people beyond the Arctic? We propose two primary linkages that connect near-surface changes to the global system. First, one of the goals of our research is to understand how changes in the near-surface environment are both driven by and feedback to the Arctic climate system by altering the surface energy flux and fluxes of greenhouse gases. It is through changes in these fluxes that local, regional, and global changes in the atmosphere will be effected. Examples of changes to be considered include changes in cloud cover regimes, storm tracks, frequencies, and intensity, and global teleconnections. For example, draining of thaw lakes will lead to large changes in surface heat, moisture, and carbon fluxes all of which can impact local to global scales of the climate system. Influences on the Arctic climate system are one critical avenue by which patchy, small-scale changes within the arctic influence the global climate system (red arrows; Figure 1). Second, as mentioned in the previous section, policy-making institutions are described in our conceptual model (Figure 1) as the primary driver of industrial development. Because the policies that determine patterns of development in the Arctic primarily originate beyond the Arctic (and are primarily determined by the needs—e.g., oil consumption—of people who live far from the Arctic), this is an important connection between the Arctic and the global system.

Linkages with other groups

The ideas and processes summarized in this document do not exist in isolation. As we have developed our ideas, it has become clear that there are a number of existing groups investigating similar or related topics. We provide a summary of those groups here. As the science planning process proceeds, formal coordination of activities among groups should be promoted in order to reduce redundancy and make the most effective use of areas where interests overlap.

1. <u>Complexity and Synthesis in Arctic Hydrology Community of Practice</u> (Alessa et al.): The Hydrology Co-OP clearly overlaps with our science priorities by addressing issues of freshwater dynamics and availability as they interact with human use and activities.
2. <u>NOAA's State of the Arctic Initiative</u>: Oceanographers at NOAA are currently preparing a report on the <u>State of the Arctic</u>. Their ongoing efforts to monitor sea ice thickness and extent may cover many of the areas identified above as being necessary research efforts to document patterns and mechanisms of changes in sea ice cover.

3. Synthesis of Arctic System Science (SASS) projects including but not limited to the project: “Greening of the Arctic – synthesis and models to examine the effect of climate, sea-ice and terrain on circumpolar vegetation changes” (below).
4. Greening of the Arctic initiative (Walker et al.): NSF has funded at least three related research projects exploring aspects of land cover change (and in some cases links to sea ice dynamics) in the arctic. These projects will contribute to the goal of documenting and understanding patterns of land cover change.
5. Human Dimensions of the Arctic System: Understanding the role of humans within and beyond the Arctic, as both drivers of and responders to change, is one of the primary objectives of this prospectus, so our Co-OP has clear linkages to the HARC initiative.

Appendix 1. Members of the Near-Surface Processes Community of Practice

Andrea Lloyd, Middlebury College, VT (paleoecology of treeline environments)
Ken Hinkel, University of Cincinnati, OH (lakes as primary geomorphic agent)

Lilian Alessa, University of Alaska, Anchorage, AK (human dimensions, complex systems)
Richard Beck, University of Cincinnati, OH (thaw lake sedimentology, remote sensing, IT)
Jim Bockheim, University of Wisconsin, WI (thaw lake basin soils)
Syndonia Bret-Harte, University of Alaska, Fairbanks, AK (plant ecology)
Chris Burn, Carleton University (thaw lake geomorphology)
John Cassano, University of Colorado, CO (polar weather and climate)
Chris Cuomo, University of Georgia, GA (social-natural science interactions)
Dirk Derksen, USGS, Anchorage, AK (hydrology and water fowl)
Claude Duguay, University of Alaska, Fairbanks, AK (remote sensing of thaw lakes)
Wendy Eisner, University of Cincinnati, OH (paleolakes, indigenous knowledge)
Eugenie Euskirchen, University of Alaska, Fairbanks, AK
Craig Fleener, Council of Athabaskan Tribal Governments, AK
S. Craig Gerlach, University of Alaska, Fairbanks, AK
Larrry Hinzman, University of Alaska, Fairbanks, AK (thaw lake changes and consequences)
Henry Huntington, Huntington Consulting, AK (macro sociology related to thaw lakes)
Ben Jones, USGS, Anchorage (thaw lake change with remote sensing, GIS)
Steve Kokelj, Indian and Northern Affairs Canada (lake water chemistry)
Scott Lamoureux, Queens University (paleoclimatology, paleohydrology of thaw lakes)
Carl Markon, USGS, Anchorage, AK (thaw lakes and water fowl)
Eric Maurer, University of Cincinnati, OH (extant and paleolakes, synchronous changes)
Glen MacDonald, UCLA
Martin Miles, Environmental Systems Analysis Research Center, CO (sea ice and circumarctic marginal seas)
Jeff Munroe, Middlebury College, VT (lake erosion and sedimentation processes)
Maribeth Murray, University of Alaska, Fairbanks, AK (archeology, human dimensions)
Fritz Nelson, University of Delaware, DE (permafrost, spatial analysis and statistics, spatiotemporal patterns of change)
Nicolai Panikov, Stevens Institute of Technology (microorganisms in cryogenic settings, methanogenesis)
Kim Peterson, University of Alaska Anchorage, AK (thaw lakes as agents in landscape evolution and vegetation succession, biogeochemical changes)
Joshua Schimel, University of California Santa Barbara, CA
Gaius Shaver, Marine Biological Laboratory, MA
Larry Smith, UCLA (remote sensing of thaw lakes—western Siberia in continuous and discontinuous permafrost)
Michael Steele, University of Washington, WA
Heidi Steltzer, Colorado State University, CO
Craig Tweedie, University of Texas at El Paso, TX (ecology, local variation in plant communities over time, remote sensing, IT)

Donald (Skip) Walker, University of Alaska, Fairbanks (vegetation ecology)
Jeffrey Welker, University of Alaska, Anchorage, AK (terrestrial ecology, biocomplexity, thaw lake succession)
Daniel White, University of Alaska, Fairbanks, AK (hydrology)
Tingjun Zhang, National Snow and Ice Data Center, CO (atmosphere, lake development interaction, lake freezing depth and effects, lake drainage consequences)

AC Liaisons:
Craig Nicolson, University of Massachusetts, MA
Matthew Sturm, Cold Regions Research and Engineering Laboratory, AK