

## SEARCH 5-Year Goals and Goal Activities

*[text from proposal and website]*

### Improve Understanding, Advance Prediction, and Explore Consequences of Changing Arctic Sea Ice

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#### Introduction

Arctic sea ice extent has been well below normal since 2007. Climate models suggest that this trend signifies a transition towards an Arctic Ocean with greatly diminished or absent summer ice cover by mid-century or earlier. Significant reduction in summer sea ice will have substantial repercussions, including extended open-water seasons fostering offshore resource development and increased maritime activity, changes in the behavior and health of marine mammals, and impacts on arctic and sub-arctic weather patterns. Predictions of sea ice changes will have large uncertainties without sustained observations; improved understanding of ice, ocean, land, and atmospheric processes; and advances in coupled and system models.

This goal addresses urgent and timely needs for improved sea ice information and will help resolve the following questions:

- Why the sea-ice is diminishing and what processes determine the rate of change?
- What are the linkages between a changing polar region and lower latitudes?
- When can a seasonally ice-free or greatly ice-diminished Arctic Ocean be expected?
- What are the most important impacts of sea ice loss on social-ecological systems?

The scientific and societal relevance of improved understanding and response to a changing arctic ice cover has been underscored by a variety of planning documents. In focusing a set of SEARCH activities on sea ice, we build on past interagency activities such as the SEARCH Sea Ice Outlook, as well as:

- NOAA's Arctic Vision and Strategy, which has improved sea-ice prediction at the top of its goals: [http://www.noaanews.noaa.gov/stories2010/20100519\\_arctic.html](http://www.noaanews.noaa.gov/stories2010/20100519_arctic.html)
- The National Ocean Policy strategy document that references the need to improve sea ice prediction and to assess its impacts on arctic ecosystems and human activities: <http://www.whitehouse.gov/administration/eop/oceans/implementationplan>
- The priorities set forth in the U.S. Arctic Research Commission's report on Goals and Objectives for Arctic Research: [http://www.arctic.gov/publications/2011-12\\_usarc\\_goals.html](http://www.arctic.gov/publications/2011-12_usarc_goals.html)
- The International Study of Arctic Change's (2010) recent science plan, which underscores the central role of sea ice in modulating arctic environmental and socio-economic change: <http://www.arcticchange.org/publications;>
- The 2009 National Presidential Directive on Arctic Region Policy: <https://www.hsdl.org/?collection/stratpol&id=pd&pid=gwb>; and
- The IARPC 5-year plan that defines interagency efforts related to sea ice research and forecasting: [http://www.nsf.gov/od/opp/arctic/iarpc/arc\\_res\\_plan\\_index.jsp](http://www.nsf.gov/od/opp/arctic/iarpc/arc_res_plan_index.jsp)

In keeping with the SEARCH vision and mission, the objectives listed below focus on areas where interagency approaches will improve understanding and prediction of arctic sea-ice change and its consequences.

### **Objectives (5-year time frame)**

#### **1. Improve the understanding of atmosphere, sea-ice, and ocean system interactions through a combination of enhanced observations and process-based modeling studies**

1.1. Develop suitable observational and modeling frameworks to identify and quantify the causes of sea ice variability and long-term decline.

1.2. Develop interagency and international support for year-round, coordinated atmosphere, sea-ice, and ocean observations in the sea-ice environment of the central Arctic Basin.

1.3. Identify and assess the impact of model uncertainties in key disciplinary and interdisciplinary processes on simulated intra- and inter-annual sea-ice variability. These processes include arctic clouds and their radiative impacts, sea-ice albedo changes, surface energy fluxes, vertical momentum transfer, and ocean vertical heat transport.

1.4. Develop and facilitate community efforts to incorporate advances made via observational and process-based modeling studies into larger-scale models.

#### **2. Improve sea ice prediction from daily to decadal timescales**

2.1. Develop interagency and international support for the [SEARCH Sea Ice Outlook](#) to expand contributor base, incorporate and advocate for needed multi-disciplinary observations, conduct assessments of predictive success, improve forecasts through synthesis of methodologies, and develop additional products.

2.2. Define a cross-agency Arctic Observing Network (AON) implementation plan that identifies critical gaps, ensures optimal observation deployment, enhances understanding of sea-ice change, and facilitates sea ice predictions across time and space scales. Identify research gaps and needs, including multidisciplinary studies and the integration of observations and modeling perspectives to improve forecast products; work with agencies to implement activities to fill research gaps.

2.3. Develop interagency and international support for enhanced observations of the arctic atmosphere via buoys, soundings, etc. in order to constrain, evaluate, and improve operational model performance in the central Arctic.

2.4. Integrate AON sea-ice measurements into global observational networks and data assimilation efforts through national and international mechanisms, e.g., [SAON](#), [CliC Arctic Sea Ice Working Group](#), an Arctic Observing Summit.

2.5. Contribute to national and international activities on sea ice forecasting and science needs (e.g., [NAS 2012](#)).

2.6. Assess the present and evolving state of the ice cover, examine overall predictability of the sea ice system, and improve and evaluate predictive methods and success across timescales. Develop cross-disciplinary scenarios to explore trajectories towards a seasonally ice-free Arctic Ocean.

2.7. Support a sea ice forecasting "Community of Practice" that addresses all forecast scales.

### **3. Explore the breadth of consequences of a seasonally ice-free Arctic Ocean across human and natural systems.**

3.1. Develop the capability to link sea ice prediction products to measures of change in marine ecosystems and impacts on arctic communities across temporal and spatial scales—from local to regional to basin scales.

3.2. Build on the [Sea Ice for Walrus Outlook](#) to determine specific information needs of stakeholders and modify standard ice prediction products where possible to address these needs.

3.3. Prioritize observational sites for investigating linkages between sea ice, marine ecosystems, and impacts.

3.4. Develop suitable measures of marine ecosystem change; identify at-risk infrastructures and ecosystem services.

3.5. Advance research on the interactions between arctic sea ice and societal aspects, such as energy and large-scale resource development, transportation, territorial issues, and impacts on ecosystems and living conditions of arctic residents.

### **4. Assess how arctic sea-ice changes interact with mid-latitude weather and climate**

4.1. Identify the impacts of a changing climate on sea ice loss; sea ice loss on patterns of atmospheric circulation and precipitation; oceanic circulation both within and beyond the Arctic, including the meridional overturning circulation in the Atlantic Ocean; and weather patterns in middle latitudes.

4.2. Communicate the importance of uncertainties and potential surprises and develop a probabilistic framework for use by decision-makers.

4.3. Advance research on the interactions between arctic sea ice and global physical systems such snow cover extent, ocean and atmospheric circulation patterns, and mid-latitude effects.

#### **Activities**

Core activities for this goal are (i) assessing the predictability of summer Arctic sea ice extent, thickness and properties on seasonal to decadal timescales and improving ice forecasts, and (ii) exploring consequences of the changing ice cover on Arctic ecosystems, the global climate system, and people.

**Ongoing Activities:** Through **ongoing** work led by SEARCH in partnership with US and international programs (World Climate Research Program, Climate and Cryosphere, CliC; World Meteorological Association Polar Prediction Project; and others), the sea ice prediction component has already made significant progress, resulting in the establishment of two communities of practice centered around seasonal pan-Arctic prediction (SIO; Calder et al. 2011) and regional information products related to ice use and marine mammal habitat (SIWO; Eicken et al. 2011b). These communities support their activities by leveraging a broad range of international resources, and developing partnerships with agencies (e.g. NSF; NOAA, National Weather Service; NASA IceBridge flights) and others (Eskimo Walrus Commission). The activities generate data products and sea ice forecasts; surveys and interaction with users indicate that these products are used by residents from coastal communities, resource managers and to a lesser extent industry. We anticipate that community activities can be sustained using existing funding opportunities. The team will leverage past and current research projects focused on how rapid Arctic change is affecting local ecosystems and the climate system beyond the borders of the Arctic. Gaps in our knowledge of these connections will be identified, prioritized, and explored for possible agency-funded investigations.

**Collaborative Scenario Development “Arctic Futures 2050”:** The framework and activities are part of an iterative process where, (1) stakeholders identify questions of concern related to consequences of an ice-diminished Arctic by 2030-50; (2) the research community develops independent scenarios of ice-diminished Arctic Ocean futures for 2030-50 using collaborative on-line tools (e.g., model simulations); (3) stakeholders review the scenarios and potentially refine questions or ask new ones; (4) researchers explore ways in which data and information products can address stakeholder questions and further refine the scenarios; and (5) further iterations occur as necessary. Products from this activity will include scenarios presented in the form of narratives, visuals, data and information products, model output, and summary documents that are written up specifically for different audiences (e.g., policymakers, general public, transportation industry etc.). These theme-based products will then tie into the overarching KE meeting and Arctic Futures 2050 Open Science Meeting (Section 5.1, Fig. 3). Due to the pan-Arctic, international relevance of this goal, we will partner with ISAC (details in Murray et al. 2012).

**Kick-off and Knowledge Exchange Meetings:** These meetings will foster collaborative work that cannot occur without networking and building new interdisciplinary research programs. A new study from the National Academies of Science (Richter-Menge et al. 2012) provides a wealth of information about the current state and future directions of sea-ice prediction and stakeholder needs for sea-ice products on seasonal and decadal time scales. This report and stakeholder participation will guide Action Team activities and will drive the kick-off meeting, Year 2 workshop and Year 3 KE meeting (Fig. 3). Support lined up by CliC, ONR Global and others for the nascent sea ice prediction network will foster working group activities under the guidance of the Action Team and lead into KE meetings and other activities connecting sea ice change with ecological and global impacts. Outcomes will be determined by further work at the team and Working Group level to include, e.g., a synthesis of plausible consequences of an ice-diminished Arctic Ocean on ecosystems on 5-10 year time scales, analysis of the value of geographic or paleo-analogs for sea ice in a warming Arctic, summarized findings from other

research (e.g., NOAA's Synthesis of Arctic Research), and lessons for ecosystem managers, regulators, Arctic coastal communities and policymakers.

**Knowledge Exchange Fellowship:** We propose two KE fellowships that would allow (i) an agency representative to join an academic research group focusing on, e.g., links between a changing ice cover, marine mammals, ecosystems and people, and (ii) a junior researcher to work with an agency to gain insight into translation of management mandates into science questions.

# Document and Understand How Degradation of Near-Surface Permafrost Will Affect Arctic and Global Systems

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## Introduction

The arctic landscape is changing in response to climate warming. Essential characteristics of the arctic landscape are controlled by its unique climate and by the presence of permafrost. Relatively rapid degradation of near-surface, ice-rich permafrost caused by atmospheric forcing is adversely affecting human infrastructure, altering arctic ecosystem structure and function, changing the surface energy balance, and has the potential to dramatically impact arctic hydrological process and increase greenhouse gas emissions. However, processes leading to permafrost change are poorly understood.

Therefore, it is imperative to address fundamental gaps in scientific knowledge of permafrost characteristics and dynamics to support planning, management, and climate policy efforts. Specifically there is an urgent need to assess the vulnerability of permafrost to thaw and to understand the local and global feedbacks when this happens. Substantial amounts of organic matter are frozen in near-surface permafrost. An unknown portion of this material will become available for microbial processing in the future, which may result in enhanced release of carbon dioxide, methane, and nitrous oxide. Greater release of these gases from sub-sea and terrestrial permafrost will likely create a positive feedback loop in which future climate warming causes further degradation of permafrost, which releases more greenhouse gases, leading to further warming and additional degradation of remaining permafrost. Such a feedback loop could result in accelerated warming throughout the globe, which will strongly impact ongoing climate change mitigation and adaptation efforts. This feedback loop, and the potential damage and costs it could generate, highlights the strong global connections between lower latitudes and the Arctic. In particular, there is a growing realization that there are strong interactions between degradation of near-surface permafrost and dynamics of the Earth climate system and that these interactions may have substantial influences on global environmental, economic, and social systems.

Critically important science and data gaps about the causes and consequences of loss of near-surface permafrost are identified in the following objectives.

## Objectives (5-Year Timeframe)

### Science Objectives:

#### *1. Improve observation and prediction of the nature, timing, and location of permafrost thaw.*

1.1. Identify indicators of change in the state of permafrost to serve as early warning signs for possible tipping points in the state of the arctic system.

1.2. Enhance existing efforts to create a comprehensive observing system to document changes in these critical indicators and to provide data for calibration and validation of models.

1.3. Determine which components of arctic landscapes are most sensitive to permafrost thaw and pose the greatest risks to human infrastructure and ecosystem services.

1.4. Develop models and probabilistic forecasting tools to quantify uncertainties in the atmospheric drivers, surface characteristics, and soil properties that control the timing and extent of permafrost thaw in the next few decades and centuries.

1.5. Characterize the extent and rates of degradation of sub-sea permafrost.

*2. Improve prediction of how degradation of near-surface permafrost will influence the dynamics of the arctic landscape.*

2.1. Promote field and modeling efforts to predict how atmospheric forcings will degrade near-surface permafrost and alter the surface energy balance and hydrology in the Arctic, at local to regional scales.

2.2. Refine estimates of the total mass, quality, and vulnerability of soil carbon by depth and region.

2.3. Identify the key variables that are likely to control the mobility and availability of carbon, nitrogen, and phosphorus from thawed permafrost and how these and other important biogeochemical materials will be processed by microbes and vegetation.

2.4. Encourage laboratory, field, and modeling efforts to estimate the amounts of critical greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) released to the atmosphere in the future as permafrost thaws.

*3. Improve prediction of how permafrost degradation will influence fish, wildlife, and human communities.*

3.1. Determine how degradation of near-surface permafrost will affect soil stability, vegetation communities, and surface and subsurface hydrology.

3.2. Identify how these factors will influence habitat suitability and distribution and the sustainability of fish and wildlife populations.

3.3. Determine how ecosystem services that are critical to human existence in the Arctic will change. This goal ties directly to the "Society and Policy" goal.

3.4. Estimate the costs of mitigation or replacement of infrastructure that will be at risk from thawing permafrost.

## Coordination Objectives:

### *4. Identify gaps in Arctic Observing Network datasets and the resources needed to fill those gaps.*

4.1. Position SEARCH to coordinate observing efforts focused on permafrost dynamics, identify gaps, advocate for cross-disciplinary observations, and encourage individual science projects to produce data that will complement the data collected by various data collection and observing networks.

4.2. Help coordinate the exchange of data necessary for modeling studies; review how model predictions identify new needs for data from observing or data collection networks.

### *5. Identify partners who can facilitate progress on the science objectives for the SEARCH permafrost goal.*

5.1. Prioritize knowledge required to support our understanding of how permafrost degradation will affect the arctic landscape.

5.2. Work with federal agencies that have made substantial investments in research on permafrost that directly or indirectly supports SEARCH objectives.

*For example:*

i. [NASA's Carbon in Arctic Reservoirs Vulnerability Experiment \(CARVE\)](#) and [Arctic-Boreal Vulnerability Experiment \(ABOVE\)](#) have objectives that parallel many of SEARCH's objectives. In addition, NASA maintains numerous sensors on different platforms that can add substantial value to projects supported by partnering programs.

ii. [DOE's Atmospheric Radiation Measurement \(ARM\) program](#) and [Next Generation Ecosystem Experiment \(NGEE\)](#) has programmatic objectives that directly address several SEARCH science objectives.

iii. The [Arctic Landscape Conservation Cooperative \(LCC\)](#) initiative is currently supporting projects that will make existing information more readily available to the science and management community.

iv. NSF's [Office of Polar Programs](#) provides essential support for long-term observation of and basic research on permafrost.

v. [USGS](#) supports permafrost borehole and soil climate change programs.

vi. The NPS has invested substantial funding in Inventory and Monitoring programs within the Arctic Parks system, which cover a substantial portion of the Alaskan Arctic region.

5.3. Explore whether industry partners would be willing to share proprietary data that could help fill gaps about the spatial (and perhaps temporal) distribution of permafrost characteristics.

## Stakeholder Objectives:

### *6. Improve delivery of information and knowledge about change in the arctic landscape to stakeholders.*

- 6.1. Ensure a steady flow of information about the status and findings of permafrost-related science efforts.
- 6.2. Develop effective means to communicate findings and progress in ways that appeal and are useful to the public and to non-technical decision makers.

### *7. Create opportunities to receive feedback about permafrost degradation from stakeholders.*

- 7.1. Identify opportunities and mechanisms to ingest experience and knowledge that could help achieve the Science Objectives.

## Activities

Briefly, this goal is composed of science, coordination, and communication objectives. The science objective has three main themes: (i) improve observation and prediction of the nature, timing, and location of permafrost thaw; (ii) improve prediction of how degradation of near-surface permafrost will influence the dynamics of the Arctic landscape; (iii) improve prediction of how permafrost degradation will influence fish, wildlife, and human communities. Each theme will be managed by independent Working Groups put in place by the Action Team with guidance from the SSC.

**Related National and International Activities:** Opportunities for progress toward this goal will benefit from linking with ongoing US activities such as the Permafrost & Carbon Research Coordination Network (RCN), NASA's Carbon in Arctic Reservoirs Vulnerability Experiment and Arctic-Boreal Vulnerability Experiment, Department of Energy's Atmospheric Radiation Measurement program and Next Generation Ecosystem Experiment - Arctic (see letter of support in Supplementary Documentation), and Department of Interior's Landscape Conservation Cooperative initiative. There are a number of international activities and networks, some currently with U.S. participants, that could also be linked, such as the Global Terrestrial Network for Permafrost, the Circumpolar Active Layer Monitoring program, the Changing Permafrost in the Arctic and its Global Effects in the 21st Century project, and the Arctic Monitoring and Assessment Program of the Arctic Council. Currently these initiatives are only loosely coordinated. SEARCH can facilitate their coordination, seek additional national and international partners (especially in industry), and develop outreach and education materials based on a synthesis of results from these projects that can be used to inform critical stakeholders and decision-makers.

**Working Groups and Community Meetings:** After the kick-off meeting each working group will hold an initial community meeting to assess the state of the art in research for their theme, identify the areas or specific topics most important to advance the science, and lay out a first coordination and activities plan (Fig. 3). As is the case with Action Teams, each Working Group will interact primarily via email and conference calls, along with an annual face-to-face

meeting. The community-wide, open meetings in Years 2 and 4 will help define and review the focus and progress, and to summarize the results.

**Scenario and Data Product Development:** Each Working Group will engage with key Arctic stakeholders, agencies, and the research community to identify a set of scenarios for likely impacts of permafrost degradation on ecological and human communities. Additional expertise and guidance will be provided by the Action Team for Goal #4. The scenarios will be used to identify where data already exist to address the community-generated scenarios and where tangible, urgent research questions could be addressed in the short-term. Outcomes from these activities will allow working groups to facilitate the development of potential partner-funded research projects to develop the data products needed to address the scenarios defined by the community. In Year 5, the Action Team will create a summary report that provides a community view on the trajectory of future permafrost change and the likely impacts on Arctic and global systems. The report will summarize the accomplishments of the Goal #2 theme, evaluate the scenario analyses, describe available data products, and outline additional research needed to address the next priorities as SEARCH continues to evolve (the latter in coordination with IARPC and USARC).

**Knowledge Exchange Fellowships:** We propose to coordinate at least two extended stays by an agency representative (e.g., USGS, USFWS) with an academic research group and the placement of at least two junior permafrost researchers with a partnering agency.

**Research Coordination Activities:** We will build on the successful Permafrost & Carbon RCN. This network has taken the first steps to coordinate the community of researchers who focus on carbon dynamics in the permafrost zone, and to synthesize scientific information into datasets useable by regional and global models. The Action Team will expand that coordination (facilitated through the community meetings and scenario development activities) to include the broader context of permafrost research, including changes in permafrost temperatures, permafrost extent, and landscape evolution and also facilitate connections with potential stakeholders to include community leaders, industries, non-governmental organizations, and policy-makers. As an outcome of increased research coordination and synthesis, the Working Groups will be able to evaluate how scientific information and knowledge is assimilated by potential end users and will seek partner funding to begin to address questions that also meet end users' interests. An ongoing activity within ACADIS to benefit the activities is the development of a data "showcase" focused on borehole temperature data, designed to standardize data formats from automatic loggers to facilitate broader data reuse.

**Communication:** In addition to communication and outreach activities (see 5.1), we also propose to produce and circulate an annual "State of Permafrost Research" report that summarizes Working Group progress, and observations for existing networks. This product will assist in the location, analysis and digestion of important and useful existing permafrost data and will be designed for use by influential, non-technical audiences.

## **Improve Predictions of Future Land-ice Loss and Impacts on Sea Level**

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## Introduction

Land ice loss—especially from northern hemisphere glaciers and the Greenland ice sheet—now exceeds thermal expansion in its contribution to rising sea level. While the loss of glacier mass has continued for the past few decades with a slight increase in recent years, the rate of mass loss from the Greenland ice sheet has dramatically increased in the past decade and continues to increase. These rapid changes are the result of increased discharge from grounded ice into the ocean and from increased ice melting, which more than outweigh increases in surface accumulation. In light of these observational facts, it is unsettling that neither quantitative prediction of future land ice loss nor credible estimation of an upper bound of future sea level are possible (IPCC, 2007). Correcting this situation requires a predictive understanding of the processes responsible for land ice loss.

Greenland contains enough ice to raise sea level an average of 6.5 meters. Glaciers and ice caps, occurring mostly in the Arctic, could contribute an additional 0.35 meters. Roughly one third of people live at or near the coast and will be directly affected by rising sea level. The direct impacts of a one-meter sea level rise include the displacement of over 100 million people, loss of nearly one trillion dollars in global gross domestic product (GDP), and the flooding of 2.2 million km<sup>2</sup> (Anthoff et al., 2006). Effective mitigation or adaptation strategies to respond to higher future sea level require credible and accurate projections of future land ice loss.

## Objectives (5-year time frame)

### 1. Determine the impact of ocean waters on tidewater and outlet glaciers

Observations of the spatial patterns and magnitudes of land-ice loss indicate the dominant role that ocean heat has in forcing increased ice discharge. Process studies that include circulation of the water near the ice, rapid melting of floating glacier tongues, calving at the glacier terminus, and the glacier's response (terminus position and changing elevation and velocity field) as these changes propagate inland are at an early stage.

1.1. Collect bathymetric data proximal and sub-glacially on a number (5-10) of large and/or recently responsive tidewater glaciers, including ice sheet outlet glaciers.

1.2. Develop, adapt, and deploy oceanographic instrumentation to monitor water properties in the vicinity of active tidewater glaciers. Link oceanographic measurements with simultaneous measurements of ice flow and calving.

1.3. Monitor glacier elevation and velocity to quantify the strength and extent of glacier response to oceanic changes.

1.4. Expand modeling efforts to simulate the intense interactive processes at play between ocean and ice in narrow fjords.

1.5. Through a combination of existing observations and new models, link oceanographic circulation on continental shelves (extending into the fjord environments) with oceanographic conditions in the deeper ocean and atmospheric patterns.

## **2. Determine the processes controlling the intra-annual and inter-annual variability of land ice discharge**

It has recently been discovered that meltwater formed at the surface of an ice sheet can cause a large and sudden increase in ice flow speed. More generally, the dynamic interaction of subglacial water flow with the overlying ice leads to multiple processes that either increase ice flow through lowered basal friction, or decrease ice flow through enlarged subglacial channels that lower effective pressures. A new functional relationship between the forcing effect of surface meltwater and ice flow must be determined based on extensive field observations to properly incorporate this effect in predictive models of future ice sheet behavior. Basal resistance can vary for non-hydrologic reasons such as deformation and sedimentation of subglacial material, yet the impact on glacier flow speed is very poorly understood. For the narrower outlet glaciers, or those with extremely low basal shear stresses, the lateral resistance of slower moving ice adjacent to the glacier can dominate the glacier's flow speed.

2.1. Collect and analyze new data on surface melt fluxes; the propagation and development of surface, englacial, and subglacial hydrologic networks; and the corresponding three-dimensional ice motions over multiple seasons and years. Projections of surface melt can then be extended to estimates of changing ice discharge.

2.2. Explore the subglacial environment, for example with advanced ice-penetrating radar systems, to assess resistive stresses that modulate ice flow rates.

2.3. Monitor deformation and thermal conditions within glacier marginal areas over seasonal and interannual time scales to quantify the sensitivity of outlet glacier discharge to changes in the glacier margins.

## **3. Improve predictions of pan-arctic surface precipitation and methods to accurately downscale precipitation patterns to the glacier basin scale**

Precipitation and melting are major components of determining the overall growth or loss of land ice. Nearly half of the ice loss experienced by the Greenland ice sheet during the past 50 years is attributed to changes in its surface mass balance (sum of all accumulation effects minus all ablative effects). Meteorological modeling of precipitation patterns over the large ice sheet are robust in the relatively broad, featureless interior (for example, with Regional Atmospheric Climate Model (RACMO)), but are more difficult at the mountainous coast and very poor in the alpine regions occupied by much of the remaining arctic land ice. Global circulation models provide the best predictions of future precipitation magnitude and distribution but lack spatial detail. Downscaling general circulation model/global climate model (GCM) output, or even output from regional climate models, such as RACMO, to account for the influences of local orography is poorly developed and must be improved. This is a relatively specialized area of climate modeling, but requires attention before it becomes the limiting uncertainty in projections of future land ice loss.

3.1. Meteorological modeling of alpine environments should be expanded to include the various components of glacier accumulation and ablation.

3.2. Test areas where densely sampled data in both space and time exist should be incorporated into meteorological models at both the local scale (0.1–1 km) and meso-scale (10–100km) to investigate accurate downscaling strategies.

#### 4. Quantify the regional pattern of relative sea-level change driven by the predicted pattern of land ice loss

The magnitude of future sea level is usually stated as a globally averaged value. Regional changes in sea level can vary up to many tens of percent from the global mean, depending on how additional water from lost land ice and thermal expansion of the upper mixed layer of the ocean are distributed by ocean currents and the changes in the gravity field resulting from changes in mass redistribution (Mitrovica et al., 2001). Because much of the expected land ice loss is sourced in various locations distributed across the Arctic, the variability of sea level change is expected to be particularly large in the Arctic.

4.1. Global gravity models should be employed to explore the possible patterns of isostatic (i.e., local) sea level change. Recent observations of ice mass loss can be extrapolated to future decades. Along with predictions of possible future land ice loss, these future patterns provide a rich sample space within which ranges of possible and likely sea level change across all arctic coastlines.

4.2. The ever-increasing set of observations of local sea level can be compared with predictions based on the observed pattern of land ice loss to improve the veracity of gravity models.

#### Activities

Progress in this goal requires a multi-faceted approach as the environmental science involves not only ice and ocean processes, but also atmospheric dynamics and geodesy, and while the topic intersects the interests of many funding organizations, it falls fully within none. Thus it is imperative that the funding agency representatives be engaged in the discussion leading to an integrated, multidisciplinary research strategy so that a coherent, feasible and meaningful research program is formulated. Specific Working Groups have yet to be defined but likely will be led by scientists with expertise in the areas of atmospheric dynamics (or coupled-climate modeling) and geodesy as well as stakeholder representatives of groups directly impacted by sea level rise (e.g., coastal communities, fisheries or coastal industries and perhaps the US Navy), so that the Action Team covers not only the environmental processes at play, but also represents those impacted by rising sea level.

**Participation in ongoing national and international activities:** SEARCH's integrated, end-to-end approach will complement existing activities related to the land ice/ sea level goal. It will leverage existing reports defining necessary science (e.g., the recent white paper from the U.S. CLIVAR Working Group on Greenland Ice Sheet/Ocean Interactions; U.S. CLIVAR 2012), informal discussions held to discuss the establishment of a new observational network, and an upcoming U.S. CLIVAR and other agencies-sponsored workshop on Greenland Ice Sheet mass change.

**Kick-off and Knowledge Exchange Meetings:** The initial meeting will help participants see the Land Ice/Sea Level topic through new eyes and better appreciate the financial and technological limitations of what is possible. Broad participation during the meetings is encouraged, and some meeting talks may be webcast. The outcomes of this meeting include specific plans that define what measurements must be undertaken, specific recommendations about where to undertake these studies, how to maintain these measurements and what products the studies must produce for which target audiences. A timetable will be established among the participants and agencies against which acceptable progress can be judged. This plan and timetable, then, define the tasks and pace of separate Working Groups. Meeting discussions may also assist funding agencies to identify an appropriate topic, timing, and scale of research solicitations.

**Working group activities:** These cannot be specified at this time, but current research provides a means to anticipate some of the tasks around which Working Groups might form. In the case that the initial meeting identifies two particular fjords (say, one in Greenland and one in coastal Alaska) that present a simple geometry or offer historical data or hold some other advantage as research sites, then an interdisciplinary Working Group might coalesce around each site with investigators skilled in establishing a suite of oceanographic instruments to be deployed at the near-ice and near continental-slope-break regions as well as on-ice GPS and meteorological sensors. Local residents could also be involved in some of the instrumentation maintenance (led by a post-doctoral researcher); and geodesists may contribute various past and future scenarios of local sea level rise to compare with local history and to give a sense of what the future might hold. Another Working Group might focus on the broader pattern of net sea level change, accounting for rates of uplift and sea level change, to identify and work with stakeholders in the most vulnerable areas to develop mitigation strategies tuned to the likely magnitude and rate of shoreline intrusion.

**Knowledge Exchange Fellowship:** An example of a KE fellowship would be a junior scientist placed in a local community and charged with ensuring the quality of data collected by local residents. Such an opportunity would provide valuable experience not only in communicating the importance of data collection and analysis, but also give the researcher a view into what scientific data and analyses are most meaningful to the local residents.

**Contributions to Arctic Futures 2050 Synthesis:** It is anticipated that the Working Groups active under this topic will make a number of specific contributions to SEARCH's synthesized assessment of the state of the Arctic in 2050. Predictions of land ice loss will provide not only the obvious projections of contributions to global sea level change, but geodetic analysis will provide a regional to local distribution of relative sea level along Arctic coastlines highlighting the risk level at each location. These risks impact human health, economic well-being and community stability, thus strongly influence public policy and link to the Action Team for Goal #4. Lost land ice exposes new ground, frequently permafrost, and alters the thermal gradients of remaining ice-covered ground giving the permafrost Working Groups new areas and thermal conditions to consider. Similarly, the discharge of increasing amounts of freshwater not only affects the oceanography of the fjords fed by the discharging glaciers, but also alters the broader-scale oceanographic circulation that can have a direct impact on the presence and movement of sea ice.

