Interagency Arctic Research Policy Committee

Arctic Research Plan: FY2013 - 2017

Contributing authors: Jonathan Berkson, United States Coast Guard; Shella Biallas, Department of the Interior; Sara Bowden, Interagency Arctic Research Policy Committee; John Calder, National Oceanic and Atmospheric Administration; C. Nikoosh Carlo, National Science Foundation; Ashley Chappell, National Oceanic and Atmospheric Administration; Kathy Crane, National Oceanic and Atmospheric Administration ; Richard Eckman, National Aeronautics and Space Administration; John Farrell, Arctic Research Commission; Wanda Ferrell, Department of Energy; William Fitzhugh, Smithsonian Institution; Martin O. Jeffries, Office of Naval Research; Brendan P. Kelly, Office of Science and Technology Policy; Igor Krupnik, Smithsonian Institution; Michael Kuperberg, Department of Energy; Marya Levintova, National Institutes of Health; Adrianna Muir, Department of State; Alan Parkinson, Centers for Disease Control and Prevention; James Partain, National Oceanic and Atmospheric Administration; Robert Sanford, National Science Foundation; Sandy Starkweather, National Oceanic and Atmospheric Administration ; Simon Stephenson, National Science Foundation; Louis Tupas, Department of Agriculture ; Taneil Uttal, National Oceanic and Atmospheric Administration; Thomas Wagner, National Aeronautics and Space Administration.

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Executive Summary

The Interagency Arctic Research Policy Committee (IARPC), which consists of principals from 13 agencies, departments, and offices across the federal government, is charged with developing five-year plans for federally sponsored research in the region. For the years 2014 to 2018, the IARPC identified seven over-arching categories to form the basis of a national policy for Arctic research and that will especially benefit from interagency collaboration. They are

1. Sea ice and marine ecosystem studies
2. Terrestrial ecosystem studies
3. Atmospheric studies of surface heat, energy, and mass balances
4. Observing systems
5. Regional climate models
6. Adaptation tools for sustaining communities
7. Human health studies

Categories were chosen based on broad scientific consensus that rapid changes in climate are altering ice and snow cover with consequences for Arctic ecosystems, indigenous societies, and global climate. The research aims to prompt solutions based on sound research discovered and implemented by multiple efforts.

This plan does not include all research conducted by Federal agencies. Many important priority investigations are and will continue to be conducted within individual agencies or other interagency collaborations.

Sea ice and marine ecosystem studies

Arctic marine ecosystems appear to be moving toward new states, with the potential for short-term surprises. IARPC agencies—including the Department of Defense, Depart of Energy, Department of Interior, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and National Science Foundation—will pursue three activities that focus on sea-ice dynamics and ecosystem change.

1. *Identify and study sites where climate feedbacks are active, especially those related to albedo and radiative-balance changes, and air-sea fluxes of heat, moisture, and greenhouse gases.*
2. *Complete deployment of a Distributed Biological Observatory (DBO) in the Arctic Ocean to create long-term data sets on physical and chemical variability and ecosystem response.*
3. *Develop integrated ecosystem processes research in the Beaufort and Chukchi seas.*

Terrestrial ecosystem studies

Climate feedbacks from ongoing changes in the terrestrial Arctic ecosystems are expected to lead to further changes in global climate, while also affecting local communities' ability to adapt to changing conditions on the ground. IARPC has identified four priority activities that form a coordinated effort by the Department of Interior, National Aeronautic and Space Administration, National Science Foundation, and the Smithsonian Institution to understanding climate feedback and terrestrial ecosystem processes.

1. *Coordinate and integrate efforts, including information delivery, that contribute to terrestrial ecosystem research.*
2. *Identify and study key sites where climate feedbacks are active, including permafrost, snow, hydrates, glaciers, and ice.*
3. *Investigate the frequency and severity of wildfires in the Arctic and understand their impacts on vegetation and wildlife.*
4. *Conduct socio-economic research to understand ecosystem services as the Arctic tundra changes with increased warming to inform plans for protecting, managing, and adapting to a fragile and changing Arctic environment.*

Atmospheric studies of surface heat, energy, and mass balances

Year-to-year and longer-scale trends and variability in surface-air temperatures tend to be larger in the Arctic than in other parts of the globe. Compared with those at low latitudes, Arctic atmospheric processes are influenced by regionally unique features, such as polar night, high albedo surfaces, and atmospheric stability, which change the sign and magnitude of aerosol- and cloud-radiative forcing. Important uncertainties about these forcings provide the rationale for improving an integrated understanding of Arctic atmospheric processes.

Coordinated remote-sensing and *in-situ* observations supported by international partnerships are critical to developing regionally coherent knowledge about the changing Arctic atmosphere, as are improving process representations in models, reducing uncertainty in model outputs, and developing long-term observational data sets.

The Department of Energy, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and National Science Foundation will address these uncertainties through three tasks.

1. *Improve understanding of short-lived climate forcers (SLCFs) and their role in Arctic amplification through satellite observations long-term in-situ observations and improved modeling.*
2. *Improve understanding of processes controlling formation, longevity, and physical properties of Arctic clouds, including the effects of—and sensitivities to—aerosols.*
3. *Develop an integrated understanding of Arctic atmospheric processes, their impact on the surface-energy budget, and their linkages with oceanic, terrestrial, and cryospheric systems through improved satellite capabilities, ground-based observations, and representations of Arctic systems in climate and weather-prediction models.*

Observing systems

Changes in Arctic terrestrial and marine environments are occurring on multiple spatial and temporal scales. Over the next five years, the National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautic and Space Administration, Department of Interior, Environmental Protection Agency, Department of Energy, Office of Naval Research, and the U.S. Coast Guard will focus on nine activities to maintain and further develop an integrated national and international Arctic observing system.

1. *Use numerical models to optimize observing-system designs and iteratively combine the two approaches.*
2. *Assess local-resident priorities with respect to climate change through studies of human health and well-being, subsistence, dependence on fossil fuels, and development of alternative energy.*
3. *Develop an optimal and integrated observing system to enhance knowledge about rapid change in extent and character of Arctic sea ice.*
4. *Further develop a collaborative international network of logistical support.*
5. *Continue satellite and other observations of terrestrial ice to better understanding the processes responsible for its loss.*
6. *Maintain and further develop observations of atmospheric constituents, such as cloud-aerosol processes and surface-radiation balance.*
7. *Continue to observe ground temperatures and permafrost thawing to understand the impacts of carbon loss.*
8. *Improve access to data through the use of services such as the Advanced Cooperative Arctic Data and Information Service to ensure future* data accessibility.
9. *Develop long-term programs to integrate community based observation networks with physical and biogeochemical monitoring systems for weather, sea ice, coastal erosion, permafrost, marine and riverine resources, and terrestrial wildlife.*

Regional climate models

Models of Earth's climate are mathematical tools for understanding processes and their feedbacks, as well as for predicting and projecting climate variability and change. Improved Arctic models will enhance understanding of ongoing processes, projections of future changes, and informed use of those projections. Process studies can advance understanding in areas that are weak or unrepresented in models; resultant improvements can better guide field research and decision making.

By strongly coupling modeling and process-science research, the Department of Energy, National Oceanic and Atmospheric Administration, Department of Interior, and National Science Foundation will ensure that models reflect the best understanding of those critical systems. The effort will entail six related activities.

1. *Inventory existing federal Arctic modeling activities.*

2. *Encourage coordination to better represent Arctic processes in Earth-system models.*
3. *Build Arctic-region models to couple with regional and global approaches.*
4. *Increase Arctic-model resolution to improve prediction and inform future research and observations.*
5. *Use model-derived insights to inform process research and vice versa.*
6. *Improve understanding of the principle drivers and uncertainties of Arctic climate changes through model validation and verification.*

Adaptation tools for sustaining communities

Arctic residents are adapting to new conditions created by rapid environmental change and diverse socio-economic stressors. Over the next five years, the Department of Interior, Department of State, Environmental Protection Agency, National Science Foundation, National Oceanic and Atmospheric Administration, Department of Agriculture, and the Smithsonian Institution will assess strengths and vulnerabilities of Arctic communities facing the impacts of climate change to help provide residents, community leaders, and policy makers with the knowledge to develop strategies for successful adaptation. The effort will focus on four activities.

1. *In collaboration with local communities, develop methods for assessing community sustainability and resilience and determine the efficacy of current adaptation strategies and means for identifying unintended positive and negative outcomes.*
2. *Identify current vulnerabilities of Arctic communities and ecosystems to climate change and explore the interaction of climate vulnerabilities with socio-economic and other stressors.*
3. *Develop projections of future climate scenarios and demographic conditions to forecast potential strengths and weaknesses of Arctic human and ecological systems.*
4. *Design new research, education, and outreach tools and processes to assist Arctic communities in language and heritage preservation and in cultural revitalization efforts.*

Human health studies

Arctic indigenous peoples have shorter life expectancy, greater infant mortality, and similar rates of the leading causes of death when compared with their respective national populations. In addition to higher death rates for unintentional injury and suicide, Native peoples experience a high prevalence of infectious diseases as well as heath impacts associated with exposures to environmental pollutants, rapid economic change and modernization, and climate change.

IARPC human-health research activities planned for the next five years reflect the priorities of both the Arctic Research Commission *Goals and Objectives for Arctic Research 2011-2011* and the 2011Arctic Health Ministers meeting held in Nuuk, Greenland. They will focus on four areas.

1. *Continue to expand circumpolar surveillance and research for infectious diseases, non-communicable diseases, trauma, and injury, sanitation services, and indoor air quality to help prevent morbidity and mortality.*
2. *Continue interagency collaboration to monitor the impacts of climate change and environmental contaminants on human health and wildlife.*
3. *Continue to support research in major priority areas such as substance abuse, obesity, diabetes, and suicide, and improve cancer screening programs to reduce incidence and mortality.*
4. *Continue to engage indigenous communities and tribal groups in research activities and projects in the Arctic.*

Introduction and Background

Lead authors: Brendan P. Kelly, Office of Science and Technology Policy, and C. Nikoosh Carlo, National Science Foundation

Introduction

Meeting the nation's economic, scientific, and environmental needs in the Arctic requires research across diverse disciplines and the involvement of multiple agencies. The Interagency Arctic Research Policy Committee (IARPC), which consists of principals from 13 agencies, departments, and offices across the federal government, is charged with developing five-year plans for federally sponsored research in the region (Arctic Research Policy Act of 1984; Title I of P.L. 98-373 of July 31, 1984). Federal agencies that make up the IARPC have diverse roles in carrying out national Arctic research policy, which is articulated in National Security Presidential Directive 66 (also Homeland Security Presidential Directive 25). It mandates that the IARPC

- Meet national security and homeland security needs relevant to the Arctic region.
- Protect the Arctic environment and conserve its biological resources.
- Ensure environmentally sustainable natural resource management and economic development in the region.
- Strengthen institutional cooperation among the eight Arctic nations (the United States, Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden).
- Involve the Arctic's indigenous communities in decisions that affect them.
- Enhance scientific monitoring of and research on local, regional, and global environmental issues.

This plan describes research priorities for the next five years that are expected to benefit from interagency collaboration. As such, it does not include all research conducted by those agencies. Many important priority investigations are and will continue to be conducted within individual agencies. Federal agencies have described their priorities for Arctic research in a series of recent reports including the U.S. Arctic Research Commission's *Report on Goals & Objectives for Arctic Research 2009 – 2010* (http://www.arctic.gov/publications/2009-10_usarc_goals.html); the U. S. Navy Arctic Road Map(http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA516591); *NOAA's Arctic Vision and Strategy* (http://www.arctic.noaa.gov/docs/NOAAArctic_V_S_2011.pdf); USGS's An *Evaluation of the Science Needs to Inform Decisions on Outer Continental Shelf Energy Development in the Chukchi and Beaufort Seas, Alaska* http://pubs.usgs.gov/circ/1370/pdf/circ1370.pdf; and the National Ocean Council's strategic action plan for *Changing Conditions in the Arctic* (*http://www.whitehouse.gov/administration/eop/oceans/sap*).

Whereas this document describes collaborative research among federal agencies, considerable important Arctic research is also conducted by academic, state, tribal, and non-governmental researchers. Additionally, under the auspices of the Arctic Council, U.S. federal agencies are active in Arctic research through working groups and *ad hoc* task forces. Collaborative research in this forum works towards sustainable development and environmental protection in the Arctic by studying a wide range of issues, including climate change, indigenous land use, and communications technology. Where appropriate, activities described in this five-year research plan will be conducted in cooperation with the Arctic Council and foster international cooperation.

Broad consensus in the national and international science communities identifies consequences of rapid environmental change on ecosystems and societies as the most-pressing and over-arching scientific concern in the Arctic. Diminishing sea-ice cover is expected to have consequences for global climate; diminishing ice sheets and glaciers will raise sea level; and thawing permafrost will impact infrastructure and increase greenhouse gases in the atmosphere. Therefore, we focus attention in this plan on key questions concerning change to the cryosphere and their downstream effects on the physical environment, ecosystems, Arctic inhabitants, and around the globe.

Sea ice and Arctic Ocean ecosystems

- *At what rates will Arctic sea ice diminish over the next 100 years?*
- *What will be the consequences of diminishing sea ice for Arctic ecosystems and their inhabitants?*
- *What will be the consequences of diminishing sea ice for global climate and environments?*
- *How will Arctic Ocean acidity change in coming decades?*
- *What will be the consequences of acidification for Arctic ecosystems and their inhabitants?*

Ice sheets and glaciers

- *At what rates will Arctic glaciers and ice sheets diminish over the next 100 years?*
- *What will be the consequences of diminishing glaciers and ice sheets for Arctic ecosystems and their inhabitants?*
- *What will be the consequences of diminishing glaciers and ice sheets for global climate and sea level?*

Permafrost

- *At what rates will Arctic permafrost diminish over the next 100 years?*
- *What will be the consequences of diminishing permafrost for Arctic ecosystems and their inhabitants?*
- *What will be the consequences of diminishing permafrost for global climate?*

This five-year, interagency plan focuses on seven priority areas designed to enhance the goals and objectives of federal agencies carrying out Arctic research. They are:

- Sea ice and marine ecosystem studies
- Terrestrial ecosystem studies
- Atmospheric studies of surface heat, energy, and mass balances
- Observing systems
- Regional climate models
- Adaptation tools for sustaining communities
- Human health

While this plan is specific to the Arctic, it is consistent with national priorities for research in all regions. Plans for research on environmental change associated with the changing climate, for example, were informed by consultation with the U.S. Global Change Research Program (http://www.globalchange.gov) and a draft of its Strategic Action Plan for 2012 - 2021. This plan also reflects and is consistent with actions proposed by the National Ocean Council's Strategic Action Plan, *Changing Conditions in the Arctic* (http://www.nopp.org/2011/national-ocean-council-strategic-action-plan-outlines-available-for-comment), as well as the interagency Study of Environmental Arctic Change (SEARCH) (http://www.arcus.org/search/searchscience).

Background

The Arctic Research and Policy Act of 1984 (ARPA) established the United States Arctic Research Commission (USARC) to promote Arctic research and recommend research policy for the region. In addition, it established the Interagency Arctic Research Policy Committee (IARPC) to develop national Arctic research policy and a five-year implementation plan. Chaired by the director of the National Science Foundation (NSF), IARPC consists of principal representatives from 13 agencies, departments, and offices whose staff convene monthly.

Recognizing the increasing participation of multiple agencies in Arctic research, President Obama, in May 2010, directed the IARPC to be chartered as a subcommittee of the National Science and Technology Committee. This report constitutes the committee's first deliverable since that change and subsequent revitalization under the leadership of both the Office of Science and Technology Policy and NSF.

For research planning, we follow Section 112 of the ARPA, which defines the Arctic as "all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers [in Alaska]; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain." We emphasize, however, that the Arctic is part of a global system undergoing rapid environmental changes and recognize its boundaries should be considered flexible where doing so enhances our understanding of the Arctic and its role in global processes.

Previous work of the IARPC

IARPC produced 21 volumes of the biannual journal, *Arctic Research of the United States*, from 1987 until 2007. The journal reported Arctic research in the United States as provided by

agencies and articulated as its vision the support of scientific and engineering research that implements national policy objectives, including

- Protecting the Arctic environment and conserving its living resources
- Promoting environmentally sustainable natural resource management and economic development in the region
- Strengthening institutions for cooperation among the eight Arctic nations
- Involving indigenous Arctic peoples in decisions that affect them
- Enhancing scientific monitoring and research on local, regional, and environmental issues (including their assessment), and
- Meeting post-Cold-War national security and defense needs.

Development of the five-year Arctic Research Plan

IARPC staff drafted an outline for the current plan in March 2011, which the principals reviewed in April 2011. The plan was developed by the IARPC staff representing the National Science Foundation (NSF), Department of Commerce (DOC), Department of Defense (DOD), Department of Energy (DOE), Department of Health and Human Services (DHHS), Department of Homeland Security (DHS), Department of Interior (DOI), Department of State (DOS), Department of Transportation (DOT), Environmental Protection Agency (EPA), Marine Mammal Commission (MMC), National Aeronautics and Space Administration (NASA), and the Smithsonian Institution (SI)

Arctic Research Commission staff also provided valuable help in developing the plan.

Evolution of scientific studies in the Arctic

Early scientific information about the Arctic was primarily geographic and collected by European explorers in the 18th and 19th centuries (Beechey 1831; Hall 1866; Frost 1988). For most of the following 100 years, scientific information came mainly from scattered efforts in ethnography and natural history, mostly associated with expeditions by the U.S. Signal Corps and others (Dall 1870; Ray 1885), and with management of fishing and hunting (Allen 1880; Elliot 1898).

The first intensive investigation along the Arctic coast of Alaska took place with the International Polar Year (1881–1884) when the Signal Corp occupied a research station at Barrow, Alaska (Baker 1982). In the 1940s, the Office of Naval Research established the Naval Arctic Research Laboratory at Barrow, and studies of Arctic environments have been carried out there almost continuously under administration of the Navy, the University of Alaska, and the North Slope Borough.

In the late 1950s, the federal government considered detonating nuclear devices to create a port along the Chukchi coast of Alaska (AEC 1959). The Atomic Energy Commission contracted an investigation of potential environmental impacts and, thereby, provided baseline information about the Chukchi coast of Alaska and its near-shore waters (Willimousky and Wolfe 1966). In

the 1970s and 1980s, an interagency agreement between the Bureau of Land Management (DOI) and the NOAA (DOC) created the Outer Continental Shelf Environmental Assessment Program to study the potential impacts of offshore oil development in sub-Arctic and Arctic Alaskan waters. For a decade or more, hundreds of studies looked at ice movements and deformation, mammals, birds, fish, benthos, plankton, microbiology, chemistry, oceanography, meteorology, and geology. Some of the work was eventually published in peer-reviewed literature, and all of it has been assembled by the University of Alaska (http://www.arlis.org/resources/ocseap-reports).

Through the 1980s, most research in the Arctic was by discipline, but later that decade the maturation of system science (Ashby 1956; von Bertalanffy 1972; Lawton 2001) coupled with the realization that human activities were driving rapid environmental change in the Arctic, prompted new approaches. The importance of interactions between the atmosphere, geosphere, hydrosphere, and biosphere were underscored by the International Geosphere-Biosphere Programme and helped stimulate the formation of NSF's Arctic System Science Program. Research focused on paleoenvironments and contemporary studies of interactions between ocean, land, and atmosphere. Eventually, human dimensions were included in studies of contemporary and paleoenvironments.

In 1997, an *ad hoc* group of scientists from 25 institutions called for a coordinated effort to understand rapid environmental change in the Arctic. Their efforts led to the formation of the Study of Environmental Arctic Change (SEARCH) (http://www.arcus.org/search/index.php). They produced science and implementation plans based on three main components: observing, understanding, and responding to Arctic change. The Arctic Observing Network aims to track and foster understanding of the complex, rapid environmental changes taking place in the Arctic, which rely on modeling, reconstructions of paleoenvironments, and process studies of the Arctic environment, socio-economics, cultures, and human health. Responding to change considers possible adaptive responses of Arctic communities and possible effects on people living outside the Arctic region. Rapid warming of the Arctic has led to dramatic declines in sea-ice extent and thickness with local and global impacts. Arctic sea ice influences atmospheric circulation patterns and precipitation as far south as the tropics (Budikova 2009).

Rapid changes taking place in the Arctic environment are affecting the region's biota and people directly and by opportunities and challenges posed by increased access to the region for mineral development, shipping, tourism, and military operations. Federal agencies are responding with research focused on understanding the natural systems and on addressing the impacts of their perturbation. Policy makers and regulators are under pressure to respond rapidly, and interagency cooperation in Arctic research has never been so important. IARPC, therefore, focused the current plan on research that will be enhanced by multi-agency efforts to address pressing societal needs.

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Research Initiatives

3.1. Understand sea-ice dynamics, ecosystem processes, ecosystem services, and climate feedbacks in the Beaufort and Chukchi Seas and the contiguous Arctic Ocean.

Lead Author: John Calder, NOAA

Agency Partners: DOD, DOI, NASA, NOAA, NSF

The 2011 Arctic Report Card (http://www.arctic.noaa.gov/reportcard) concludes that data collected since 2006 are sufficient to indicate a shift in the Arctic Ocean system, which is characterized by the persistent decline in the thickness and summer extent of the sea-ice cover, and a warmer, fresher, and more-acidic upper ocean. Moreover, there is growing evidence (Krupnik and Bogoslovskaya 1999; Grebmeier 2006; Gradinger, et al. 2010) that those changes are moving marine ecosystems in the Beaufort and Chukchi Seas and the contiguous Arctic Ocean toward new and generally unknown states, with the potential for short-term surprises.

IARPC agencies will work together over the next five years to enhance understanding of changing sea-ice-ocean-atmosphere interactions and feedbacks; improve sea-ice forecasting at spatial and temporal scales; and detect and understand ecosystem change. The results will enable informed decision making by users and managers of Arctic Ocean resources. Interagency research will benefit greatly from cooperation with international partners.

The work focuses on three activities.

Identify and study sites where climate feedbacks are active, especially those related to albedo and radiative-balance changes, and air-sea fluxes of heat, moisture, and greenhouse gases.

Why do this: The minimal extent of summer Arctic sea ice from 2007 to the present has fallen below the previously established trend line for the period 1979 through 2006 (Arctic Report Card, 2011: http://www.arctic.noaa.gov/reportcard), and the rate of sea-ice loss exceeds that projected by coupled climate models (Stroeve et al. 2007). Continued loss of sea ice will affect marine and terrestrial ecosystems, coastal communities, maritime transportation, natural resource development, regional and global weather and climate, and homeland and national security. Understanding and predicting the consequences of continuing sea-ice loss on the marine ecosystem will require better understanding of the Arctic Ocean environment and processes to improve sea-ice forecasts and predictions at a variety of spatial and temporal scales.

The sea-ice edge during the Arctic spring through fall seasons is dynamic with rapid and large location changes in response to amount of snow cover; clouds, solar radiation and albedo; winds and ocean waves; and air and water temperatures. Interactions and feedbacks among those variables, from local to regional scales, are believed to amplify Arctic-wide climate change and

sea-ice retreat (Perovich and Richter-Menge 2009). Better knowledge about such feedbacks is vital for understanding ice-air-ocean system processes, improving daily to seasonal weather and sea-ice forecast models, and increasing the accuracy of longer-term sea-ice and climate projections.

Recent evidence (Shakova et al., 2010) indicates that methane is being released from or through thawing permafrost under shallow coastal seas. The amount of methane available for release is potentially very large, but there are no data on the current rate of release throughout the Arctic or how the rate might change. Recent work on the Beaufort Sea shelf found no conclusive evidence of massive methane venting from subsurface systems (Coffin et al. 2010). The shallow shelves off northern Siberia and around the McKenzie Delta are important marine areas for methane research, and partnerships with Russia and Canada are essential to this work.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Improved forecasts to support safe operations and ecosystem stewardship and to reduce uncertainty in predictions and projections for better informed policy and decision making at local, state, national, and international levels
- Improved daily, weekly, and seasonal weather and sea-ice models and forecasts to fill a critical gap in marine weather and climate services with benefit for community and subsistence activities, management of protected marine resources (including sea ice-dependent species), marine navigation, and industry operations
- Reduced uncertainty and increased accuracy of sea-ice projections and understanding of how newly sea-ice-free areas influence weather and climate, which will lead to sustainable infrastructure and community planning and aid in projecting of regional and global climate impacts forced by changes in the Arctic
- Improved understanding and ability to forecast (based on both *in-situ* and remotely sensed data) of Arctic environmental change
- Improved estimates of the contribution of Arctic methane releases to climate warming

Milestones:

- Report of a workshop on sea-ice forecasting (NOAA, FY2012)
- Report of a workshop on the future of Arctic sea-ice research and forecasting, National Academy Polar Research Board (NASA, intelligence community, ONR, FY12012)
- Investigate the marginal ice zone:
  - (1) Emerging Dynamics of the Marginal Ice Zone (ONR, FY2012-2016)
    - Science and field experiment planning; equipment development and testing (FY2012-FY2013)
    - Main field experiment in the Beaufort Sea (FY2014)
    - Data analysis and synthesis (FY2015-FY2016)
  - (2) Marginal Ice Zone Observations and Processes Experiment (MIZOPEX): (NOAA, FY2012-FY2013)

- Investigate sea-state and boundary layer physics in the emerging Arctic Ocean (ONR, FY2013-FY2017).
  - Science and field experiment planning; equipment development and testing (FY2013-FY2014)
  - Main field experiment in the Beaufort and Chukchi seas (FY2015)
  - Data analysis and synthesis (FY2016-FY2017)
- Initiate inter-agency activity to improve application of remote sensing and buoy/mooring data to sea-ice forecasting, NOAA (FY2012)
- Investigate characterization of the circulation on the continental shelf areas of the Northeast Chukchi and Western Beaufort Seas (BOEMRE, FY2012, pending approval).
- Initiate interagency evaluation of trends and significance of methane flux to the atmosphere in Arctic regions (NOAA, USGS, Navy-NRL, DOE-NETL, FY2015).
- Initiate a dialogue with *Roshydromet* and Russian Academy of Science on a potential investigation of the current rate of methane release from the shallow shelves off northern Siberia (NOAA lead with other agencies, FY2013).
- Initiate a dialogue with Canadian agencies on collaborative methane research along the Beaufort Sea coast (DOE lead with other agencies, FY2013).
- Identify optimal sites for short-term process studies underpinned by long-term observations (all agencies).

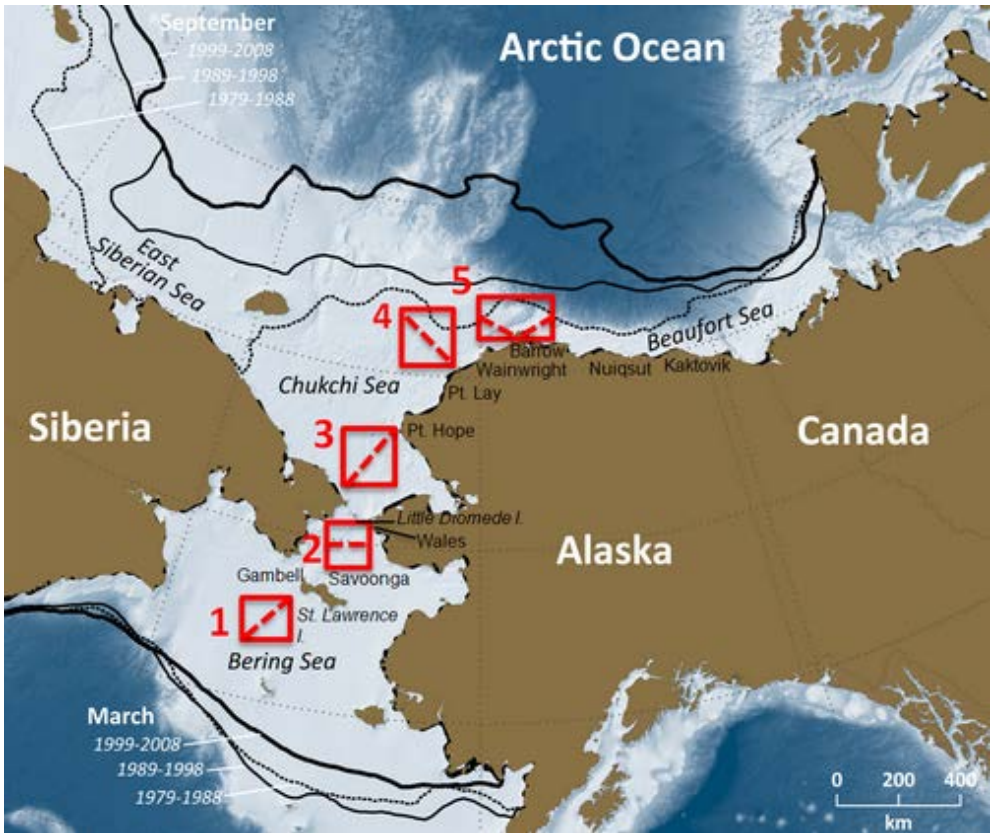
Science and Technology Gaps and Needs: New and enhanced communications technology in *in-situ* orbital and non-orbital sensors is needed to provide real-time, integrated observations and products derived from atmosphere, ice, and ocean. The sensors will support investigations of the interactions and feedbacks among variables that control sea-ice concentration, thickness and motion, and the location of the ice edge. Deployment of *in-situ* sensors and support for process studies will require coordination with and access to charter and non-charter vessels capable of operating during spring, summer, and fall. Research into interactions and feedbacks among the atmosphere, ice, and ocean requires improved process models. Improving forecasts and predictions will require models that assimilate advanced observing data and derived products; provide time-varying sea-ice concentration, thickness, and ice-edge location at high temporal and special resolution; and fully couple ice-ocean-atmosphere processes.

Complete deployment of a Distributed Biological Observatory in the Arctic Ocean to create long-term data sets on physical and chemical variability, change, and ecosystem response.

Why do this: The Distributed Biological Observatory (DBO) (http://www.arctic.noaa.gov/dbo) integrates biological and physical sampling from both moorings and ships**,** using a collaborative network of logistical support (Grebmeier et al. 2010). Remote sensing and advanced *in-situ* technologies will be critical to the observatory's success. Information from the DBO will provide a better understanding of how climate change affects Arctic biology and what steps will be necessary to improve stewardship of the Arctic marine ecosystem as human use and economic development increase. The DBO will require a multi-decadal perspective with renewal of approaches and priorities as need requires and knowledge and technologies allow.

Changes in location and timing of the seasonal ice edge can have profound effects on benthic and pelagic marine ecology and human activity (Grebmeier et al. 2012; Huntington 2009). These changes also affect the ability of ice-dependent marine mammals to reproduce and rear young on ice (Kelly 2001; Kelly et al. 2010; Cameron et al. 2010). Changes in zooplankton availability can affect distribution and abundance of baleen whales, which are important to subsistence cultures (Ashjian et al. 2010; Moore et al. 2010). Likewise, stranding of ice-dependent species on land likely reduces their survival or reproductive rate and will change their availability to subsistence hunters. Relationships among ice-edge retreat, changes in plankton dynamics, loss of summer sea ice, and foraging success of whales and ice-dependent species are poorly understood (Moore and Huntington 2008; Kovacs et al. 2011), as are the effects of these changes on Alaska Natives who depend upon such species (Metcalf and Robards 2008). The flux of mass, heat, salt, and nutrients through the Bering Strait is changing the physical processes of the Arctic Ocean. The consequences of ocean acidification, happening now and projected to be greater in Arctic waters than anywhere else, are largely unknown.

Figure 3.1.1. Four possible regional locations of Distributed Biological Observatory transect lines and stations for standard hydrological and biological measurements in the Pacific Arctic sector.



Relevant U.S. agencies (including NOAA, NSF, NASA) and international partners (including Canada, China, Japan, Korea, and Russia) will take advantage of current research programs to create a marine DBO in the region for consistent, long-term monitoring of biophysical responses in pivotal oceanographic areas along a north-south latitude (Figure 3.1.1). Each area exhibits high biological productivity, biodiversity, and gradients in ecosystem properties and direct linkages to subsistence-based coastal communities. All areas are projected to experience increased commercial use with the loss of sea ice. As sea ice retreats, the DBO will track the rate of ecosystem change and identify impacts. The DBO will provide critical information on the biodiversity of this region and a baseline for assessing how biodiversity will respond to climate change and loss of sea ice. The DBO will also provide baseline information necessary to assess and mitigate potential impacts of offshore resource development on subsistence activities. Observations will be conducted in collaboration with international partners and coordinated through the Pacific Arctic Group.

Timeframe: pilot-project and planning (3-5 years); decadal-term implementation

Expected Outcomes:

The DBO will:

- Provide a knowledge-resource base to improve the ability of resource management agencies to determine the effects of their actions on marine resources, resulting in improved conservation, protection, and management of Arctic coastal and ocean resources.
- Improve understanding of the effects of Arctic ecosystem and climate changes on subsistence cultures in the region.
- Provide information on variability and change in the physical environment at DBO sites and the associated response of planktonic, pelagic, and benthic communities to enable improved management and use of marine resources, including subsistence use of marine mammals.
- Develop or improve physical-ecosystem models that relate past variability and change in both physical and biological conditions at DBO sites and inform resource managers of potential future conditions under different scenarios.
- Aid in developing risk-averse strategies to maximize the resilience of marine ecosystems, and develop strategies to mitigate and adapt to adverse impacts.
- Increase understanding of the ecological implications of:
  - increasingly early ice-edge retreat and absence of summer sea ice
  - increased severity of storms during the ice-free season
  - ice-dependent species forced to spend time on land, including impacts of human disturbance; and
  - ocean acidification on Arctic marine ecosystems, especially plankton and calcareous benthic organisms important as prey items to subsistence species
- Increase ability to monitor and assess environmental conditions under changing climate scenarios through new collaborations and partnerships.
- Forge a connection between a U.S. observing network and similar networks of other countries.

Milestones:

- DBO partners conduct pilot research cruises (FY2010-2013) (http://www.arctic.noaa.gov/dbo/).
- AON subcommittee organizes DBO interagency working group to develop U.S. plans and priorities (NOAA, NSF, NASA, FY2012).
- Initiate a dialogue with *Roshydromet* and Russian Academy of Science on developing DBO stations in Russian territory as a compliment to those in U.S. waters (NOAA, FY2012).
- Pacific Arctic Group (PAG) meets annually to review results from 2010-2013 pilot activities.
- Report in 2014 on International DBO activities and results to date.
- Updated DBO concept and national/international plan for decadal-scale implementation release in 2014 will include identification of satellite resources that will be critical to the DBO. Ocean color, SST, SSH, SS salinity, and winds are all key measurements in the cloudy Arctic for ecosystem characterization.
- Starting in 2015, DBO partners execute decadal-scale plans and prepare periodic assessments on physical and ecological state of Pacific Arctic marine environment.

Science and Technology Gaps and Needs: The DBO will require agencies to pursue new technologies for continuous, year-round, real-time observations of key physical, chemical, and biological variables; improve coordination with and access to charter and non-charter vessels capable of working in Arctic areas during the spring, summer, and fall; enhance application of satellite- and aircraft-based sensors; and improve use of community based observations and instrumented animals.

Develop integrated ecosystem research in the Beaufort and Chukchi Seas.

Why do this: While the DBO will provide an extended time perspective on key ecosystem variables, a parallel effort is needed to identify and understand processes that control ecosystem structure and function and to determine their sensitivities to changes in physical and chemical environments. Results from process studies inform models that can be used to project future ecosystem status and allow proactive adaptation to changing conditions. Coordination of the Bering Sea Ecosystem Study (NSF) and the Bering Sea Integrated Ecosystem Research Program (North Pacific Research Board) stands as a model for how an interagency study might be organized (Bering Sea Interagency Working Group 2006).

There are numerous outstanding research questions that will benefit from an interagency approach, such as:

- How will ecosystems respond to expected continued warming and acidification of the waters in the Chukchi and Beaufort Seas and the contiguous Arctic Ocean?
- How might fluxes of mass, heat, salt, and nutrients from the Bering Strait, from the Mackenzie River, from Siberian coastal currents, or from Atlantic water intrusion impact ecosystems in the study region?

- How will ice edge ecosystems adapt to changes in location and timing of sea ice retreat and re-growth?
- Will the increased areas of open water seen in recent summers lead to seasonal deepening of the mixed layer and alter ecosystem processes?
- Will southern species establish themselves in the Arctic Ocean and might stocks approach commercial size?
- Will eastern and western species and stocks intermix, and will intermixture decrease diversity and/or adaptation?
- How well do ecosystem models describe the current state of ecosystems in the study region and what improvements are needed to enable skillful projection of future ecosystem states?
- What new observing tools or technologies are needed to improve understanding of ecosystem processes?
- How will degradation of submerged permafrost and natural gas hydrates impact ecosystems in the Chukchi and Beaufort shelf regions?
- How will increased oil and gas drilling in the Chukchi and Beaufort seas impact natural ecosystems?

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

This research will create new knowledge about the regional ecosystem, including its key components and their linkages, and insight into how it responds to perturbation. This information will help hypotheses about responses to long-term trends such as persistent loss of summer sea ice, ocean warming, and ocean acidification. Scenarios for future subsistence and commercial use of living marine resources could be constructed from the research results and serve as guides for longer-term sustained observations. Results from process studies inform models that can be used to project future ecosystem status and allow proactive adaptation to changing conditions.

Milestones:

- Conduct interagency and international workshops and consultations during 2012 to identify high priority research themes and objectives and coordinate funding and logistic plans (all agencies).
- Perform synthesis and assessment during 2013-2014 on existing data and information to provide foundation for new research activities (all agencies).
- Initiate 3-5 year research activities starting in 2014 with interagency/international results integration mechanism (all agencies).
- Conduct initial science integration conference in 2016 (all agencies).
- Conduct environmental and integrated risk assessments to evaluate the potential impacts of oil/natural gas production on ecosystems in the Beaufort Sea (DOE lead with other agencies, 2013-2014).

Science and Technology Gaps and Needs: Improved partnerships between scientists and local-knowledge holders are needed as are the means for reviewing and funding such partnerships. Improved biophysical models will be needed, along with a parallel effort to test and validate the

model outputs. Full-year investigations will create new requirements for observing platforms and data storage and transmission. New sensors, automated samplers, and autonomous vehicles will be needed to meet more-ambitious research objectives.

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3.2: Understand high latitude terrestrial ecosystem processes, ecosystem services, and climate feedbacks.

Lead Author: Shella Biallas, DOI

Agencies Partners: DOI, NASA, NSF, SI

Studying Arctic terrestrial ecosystem processes, ecosystem services, and climate feedbacks will contribute to a better understanding of the cumulative impacts of changes taking place in the region. Climate feedbacks from ongoing ecosystem changes are only beginning to be understood but are expected to lead to further changes in the global climate system while affecting local communities' abilities to adapt to altered conditions on the ground. The 2004 Arctic Climate Impact Assessment (ACIA 2005) outlined a number of high-priority science needs, including a better understanding of changes likely to occur in terrestrial ecosystems and how they will impact local communities. Currently, there are strong research partnerships among U.S. agencies operating in the Arctic. The Landscape Conservation Cooperatives and the Alaska Climate Science Center, for example, are working to implement an applied-science program to conserve Arctic natural resources.

The four research areas outlined below will further existing research participation and coordinate approaches to understanding climate feedback and terrestrial ecosystem processes and services.

Coordinate and integrate terrestrial ecosystem research efforts.

Why do this: Significant efforts have been made to coordinate and share research on terrestrial ecosystems in the Arctic. These would benefit from access to and use of existing data systems and information portals and efforts to identify gaps in dissemination of research data and information. Additionally, sharing resources and information among agencies could be enhanced through formal agreements, such as the Memorandum of Understanding between NOAA and USGS (MoU 2011).

Existing cross-agency sources of information and portals that provide a basis for comprehensive information sharing and coordination include:

- NSF Cooperative Arctic Data and Information Service (CADIS) and Advanced CADIS system (A-CADIS).
- Alaska Data Integration Working Group (ADIwg), formed to examine and address the technical barriers to efficiently integrate and share data within and among participating organizations.
- Polar Data Catalog maintained by the Canadian Cryospheric Information Network (CCIN).
- The North Slope Science Initiative/University of Alaska Geographic Information Network (NSSI/GINA).
- USGS Science Portal.
- The Arctic Council's Conservation of Arctic Flora and Fauna (CAFF), Circumpolar Biodiversity Monitoring Program (CBMP) is developing a distributed and

decentralized geo-referenced, web-based portal for communications, data archiving, and information exchange.

- Arctic Portal established as part of the International Polar Year (IPY) activities and currently maintained by Iceland and various Arctic Council Working Groups.
- Arctic, Western Alaska, and Aleutians & Bering Sea Landscape Conservation Cooperatives (LCCs) are identifying shared science needs among partners and developing collaborative strategies to prioritize and address those needs.

In addition to those interagency information sources, individual IARPC agencies (NASA, USGS, NWS) maintain substantial databases that, in turn, inform cross-agency efforts.

Timeframe: Near-term (1-3 years)

Expected Outcomes:

- U.S. federal and Alaska state agency scientists identify the five most-pressing needs for scientific research in the terrestrial Arctic, in cooperation with Arctic Council efforts.
- Existing information sharing mechanisms, such as data.gov, AON/CADIS, or the NSSI/GINA data catalog, are fully utilized by scientists in planning and implementing terrestrial-ecosystem research in the Arctic to coordinate with other ongoing and planned efforts.
- A single information delivery data hub, such as data.gov, is identified as the primary hub for accessing various portals and databases of U.S. and international Arctic research activities to provide a point of access and collaboration for research activities.

Milestones:

- Databases currently maintained by NSSI, NSF, USGS, the Arctic LCC, and non-governmental groups are made available on one website or via one access point (Spring 2013).
- A significant number of Arctic studies involve cross-disciplinary collaboration at the principle investigator level that leads to improved understanding of Arctic systems (Summer 2014).

Science and Technology Gaps and Needs: Federal agencies should agree upon and adopt a single access point to existing and future information-sharing databases and portals and share them with cooperating state, local, and international partners. Stored long-term observing data and associated information should be accessible to and easily managed by contributing partners.

Identify and study key sites where climate feedbacks are active, including permafrost, snow, hydrates, glaciers, and ice.

Why do this: A warming climate is leading to decreasing snow cover and thawing permafrost in the terrestrial environment. The Arctic cryosphere regulates local, regional, and global climate and provides vital ecosystem services to communities. Terrestrial feedbacks in a few locations have been studied in depth; still, climate feedbacks over a large area are still poorly understood (Arctic Monitoring and Assessment Program 2011).

The 2011 report, *Snow, Water, Ice, and Permafrost in the Arctic* (SWIPA), from the Arctic Monitoring and Assessment Program (AMAP) of the Arctic Council identifies a number of areas where additional U.S.-supported research could improve understanding of the cryosphere (for a summary of the 2011 recommendations and updated information about the ongoing AMAP project, see http://amap.no/swipa/). The SWIPA report concludes that the intensity of cryosphere-climate feedbacks are not well quantified, which leads to uncertain predictions of the degree and rate of changes in the cryosphere and Arctic environment. Understanding how cryosphere changes will affect Arctic communities will also be important. In particular, how will it impact migration patterns of subsistence species and the stability of infrastructure such as roads, airports, pipelines, and buildings? Additionally, more research is needed to answer questions about how climate-driven changes in the active layer, hydrology, coastal processes, rainfall, permafrost, and glacier and ice-sheet melt affect the larger ecosystem before scientists can predict how species (including those important for subsistence) will react to new conditions.

Geographical sites where climate feedbacks are observable can be identified by enhancing existing networks that build capacity for identifying, understanding, predicting, and responding to diverse environmental changes throughout the Arctic. For example, the Arctic LCC is identifying a suite of biophysical process topics most relevant to forecasting species and habitat response, which will guide recommendations for priority monitoring, activities, and modeling products. The Arctic LLC will recommend candidate sites for inclusion in a terrestrial ecosystem-monitoring network for northern Alaska that addresses the linkages between physical drivers and biological responses. Implementing those recommendations will require the combined efforts and support of multiple agencies. Also, the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT) studies 32 sites in 14 countries, including all Arctic nations.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Cross-agency agreement on geographical areas in the U.S. Arctic where additional research on climate feedbacks and impacts on the cryosphere is most needed
- Increased understanding of ecosystem responses to changing climate and cryosphere change, which informs management decisions and subsistence uses

Milestones:

- Consult with local communities on the geographical areas of traditional use that are most impacted by changes in the terrestrial cryosphere, as well as the types of

changes—permafrost thaw, coastal erosion, vegetation—most relevant to local communities (summer 2013).

- Identify and compile GIS data layers of existing climate feedback research in the Arctic and compare with areas of important traditional use (fall/winter 2012).
- Complete improved coastal map and high precision Digital Elevation Models (DEM) for western Alaska in order to better understand coastal erosion, storm surges, and sea level rise. (summer 2013)

Science and Technology Gaps and Needs: Traditional knowledge can help detect changes in terrestrial Arctic ecosystems and guide adaptation. As the cryosphere changes, climate feedbacks become more complex, changes in Arctic systems will occur more rapidly, and integrating traditional knowledge into decisions will be more difficult. Other needs include more-systematically collected information about the effects of cryospheric change on human society and greater engagement between the scientific community and Arctic residents.

Improved networks are necessary to observe many of the long-term environmental changes taking place in the Arctic, including those pertaining to climate feedbacks (see section 3.4). A better understanding of the complex interactions among the physical, chemical, and biological environments is also needed. Coordinating measures of changes in ecosystems and their components (e.g., species of concern) from *in-situ* and discrete observations with wider-ranging environmental parameters from remote instruments remains a challenge. Such coordination will improve the ability to relate geophysical change patterns to processes affecting ecosystems occurring across a range of spatial scales.

Investigate the frequency and severity of wildfires in the Arctic.

Why do this: Current and future climate changes will affect the frequency, extent, and severity of Arctic wildfires and will have cascading effects on other ecosystem processes (Final Report of the Joint Fire Study Program 2011). Wildfire is the primary disturbance in boreal forests of interior Alaska and a major disturbance in the tundra regions of the U.S. Arctic. Fire frequency and severity are primary determinants of vegetative succession trajectories and, subsequently, the rates of carbon sequestration and loss in boreal ecosystems. Fire frequency and severity are likely to increase in tundra ecosystems as plant biomass and productivity increase with the lengthening growing season. Vegetation succession following fire in tundra ecosystems, such as the Seward Peninsula, however, is not well understood (Final Report of the Joint Fire Study Program 2011). Fire regimes and impacts have been observed on fine spatial scales at point locations in Alaska, but the collective impacts of wildfire on vegetation, carbon, wildlife, air quality, permafrost degradation, and biogeochemical cycles across the landscape are poorly understood , yet critical to regional fire management strategies.

The 2007 Anaktuvuk River fire was the largest fire to take place in the U.S. Arctic since recording began in 1950 and had major implications both for local ecosystems and the global carbon system. NSF and other agencies have funded investigations of the severity of and ecological response to the Anaktuvuk River fire. That type of research, however, has not been a priority for resource managers. A recent study found the Anaktuvuk fire released carbon into the

atmosphere about 100 times faster than it usually escapes from the ground in the Arctic summer and released more than 2 million tons of CO_2 (Mack 2011). The fire burned down to the mineral soil and damaged slow-growing lichen, which drastically reduced winter forage for caribou. Because caribou foraging on winter range tend to avoid burned areas for up to 50 years (Joly 2007), large-scale burns may change seasonal distribution of the animals, thereby limiting their availability to subsistence users.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- An integrated understanding of the trends and impacts of Arctic wildfires to inform policy and land-management decisions

Milestones:

- Identify and inventory existing scientific research on Arctic wildfires (2012).
- Consult with local communities and indigenous groups on science needs pertaining to Arctic wildfires and their impacts on cultural and subsistence needs (summer/fall 2012).
- Develop strategies/projects to identify succession stages of tundra communities following a wildfire (2013).

Science and Technology: *Gaps and Needs:* While the 2007 Anaktuvuk River fire was a unique event on the North Slope, it is not clear whether ongoing climate changes will lead to additional severe fires. Paleoecological work assessing fire-deposited charcoal in lake cores is underway and should contribute to improved understanding of fire regime in that area. As fire return intervals have historically been several hundreds of years, detecting less than very dramatic changes in long-term fire regime, or fire severity, may not be possible. Credible prediction of the potential effects of changes in fire regime, or fire management policy, on caribou distribution and subsistence use will likewise be challenging. The Integrated Ecosystem Modeling project, through the Alaska Climate Science Center and the Western and Arctic LCCs, is creating a framework to link existing models to produce a single integrated platform that simulates vegetation succession, disturbance regimes, hydrology, and permafrost dynamics. Government-wide support for this work can contribute to state-wide maps that forecast ecological conditions under specified climate scenarios. Other data needs include greater coverage in lightning-strike detection, particularly in the central Arctic, and enhanced distribution of weather-station observation sites that collect temperature and precipitation data.

Conduct socio-economic research to understand ecosystem services as increased warming changes the Arctic tundra.

Why do this: Polar amplification of global environmental change is forcing local residents to address immediate needs and identify adaptation strategies for a changing environment—all while balancing social, cultural, and economic demands and expectations (see section 3.6).

Additional environmental stressors brought on by increased human activity in the area are also affecting Arctic communities. Such rapid change affects supply of subsistence foods and storage capability, integrity of local infrastructure, and social and cultural systems (http://www.arctichealth.org/ccNorthernCommunities). At the same time, residents are burdened with economic and political pressures to fulfill global energy needs.

More than 86 percent of communities in rural Alaska have been affected by serious erosion and flooding (GAO 2003), which has forced relocation at prohibitive cost and selection of sites that will remain stable indefinitely. More research is needed on the social and economic impacts ongoing environmental changes and their implications for local communities. Such information will provide the framework and data needed to develop proactive plans for protecting, managing, and adapting to a fragile and changing Arctic environment.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- A survey of the state of knowledge on terrestrial ecosystem services in the Arctic, including identification of gaps in research on the importance of ecosystem services for Northern communities
- A set of robust and reliable social indicators are established to predict, monitor, and mitigate the effects of climate change on Alaskan Arctic communities.

Milestones:

- Support the outcomes and recommendations of the Arctic Social Indicators Project (http://www.svs.is/asi/Implementation/Project%20description%20II.htm) within the U.S. by
    - Developing a meta-database, published electronically, that identifies baseline Arctic social indicators already monitored by national agencies (2013);
    - Establishing an international task force of Arctic researchers to ensure social data are collected in a way that allows statistically valid comparisons among Arctic communities (2012);
    - Collecting data on the socio-economic implications of climate change at a regional level parsed into indigenous and non-indigenous domains at 5-year intervals (beginning 2013)

Science and Technology Gaps and Needs: Socio-economic data at the village and region-level are lacking as are direct investigations of the links between cause and social effects. The mechanisms of cause and effect are often complex and multifactoral. Small population size at the village and region level may preclude acquisition of statistically significant data for some indices.

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3.3 Atmospheric studies of surface heat, energy, and mass balances

Lead Authors: Richard Eckman, NASA, Taneil Uttal, NOAA, and, Sandy Starkweather, NOAA

Agency Partners: DOE, NASA, NOAA, NSF

Year-to-year and longer-scale trends and variability in surface-air temperature tend to be larger in the Arctic than in other parts of the globe. This Arctic amplification phenomenon is recognized as an inherent characteristic of the global climate system (Serreze and Barry 2011); the causes are believed to include complex interactions associated with heat exchange between the atmosphere and ocean (with its changing sea-ice extent), meridional heat transport, and radiative forcing from atmospheric constituents. Arctic atmospheric processes are influenced by regionally unique features (polar night, high albedo surfaces, and atmospheric stability) that change the sign and magnitude of aerosol and cloud radiative forcing relative to low latitudes. Important uncertainties in the sign and magnitude of these forcings (e.g., IPCC AR4) provide the rationale for coordinating and improving our integrated understanding of Arctic atmospheric processes. This plan addresses those uncertainties through milestones aimed at improving process representations in models, reducing uncertainty in model outputs, and developing iconic long-term observational data sets.

Remote sensing and *in-situ* observations at long-term observatories complement each other and contribute to documenting as well as understanding long-term trends. NASA and NOAA remote sensing assets offer a unique resource for observing Arctic atmospheric composition and radiative forcing. DOE, NSF, and NOAA support key ground-based observatories, such as those coordinated through the International Arctic System for Observing the Atmosphere (IASOA), which provide long-term data sets and valuable resources for validating satellite observations and campaign studies. During the International Polar Year, IASOA developed a major new international observatory facility in Tiksi, Russia, that significantly extends circumpolar coverage. DOE, NASA, NSF, and NOAA field and aircraft campaigns have contributed to an integrated understanding of the Arctic atmosphere and improved model parameterizations and the value of remote-sensing data products. DOE- and NSF-supported predictive modeling contributes to long-term understanding of regional and global sensitivities to aerosol loading and cloud processes, have revealed the relative contributions of short-lived climate forcers, and have helped to develop an integrated picture of the atmospheric interactions with terrestrial, oceanic, and cryospheric systems. Coordinated approaches around the Arctic, particularly those supported by international partnerships, are critical to developing a regionally coherent understanding of both how and why the Arctic atmosphere is changing. Jointly, these activities are improving our understanding of the unique role of the Arctic atmosphere with regional and global implications.

Improve understanding of the source regions and radiative forcing of short-lived climate forcers and their roles in Arctic amplification.

Why Do This: Short-lived climate forcers (SLCFs)—including black-carbon aerosols, ozone, and methane—are atmospheric constituents with relatively short residence times (days to years), and

which are thought to have an enhanced influence on Arctic radiative forcing relative to mid-latitudes (Quinn et al. 2008). Globally, black-carbon aerosols absorb solar radiation and warm the atmosphere. In the Arctic, warming is enhanced, particularly in springtime, by bright snow and ice surfaces. Black-carbon aerosols deposited on those surfaces can contribute to reduced albedo and enhanced melt. Increased human activity and resource development in the Arctic will likely introduce new sources of black-carbon pollution to the region. The Arctic contains vast amounts of methane locked in permafrost deposits and marine hydrates, with an uncertain potential for release into the atmosphere. As a greenhouse gas, methane is four times more effective per molecule at trapping heat than is carbon dioxide. Understanding current methane emissions and potential scenarios under a warmer Arctic is imperative. Ozone is both an air pollutant that impacts human health as well as a greenhouse gas. Both Arctic and remote sources produce ozone and its precursors. Boreal forest fires and increasing human activity will increase ozone precursors in the region. Further research is required to understand sources of ozone precursors as well as the oxidation capacity of the Arctic atmosphere.

Existing agency capabilities to study SLCF include satellite instruments that monitor the long-range transport of mid-latitude pollution to the Arctic, in addition to detecting fires and their smoke plumes. These instruments measure aerosol optical depths, other aerosol properties, and collocated cloud properties. The Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging SpectroRadiometer (MISR) provide an aerosol record dating from 2000, while the Atmospheric Infrared Sensor (AIRS) provides a carbon monoxide record from 2002. IASOA network observatories include several growing proxy data sets for black carbon, as well as direct measurements of methane and ozone at limited locations. About a dozen Aerosol Robotic Network (AERONET) and AeroCan (AERosol CANada) sunphotometer sites located at latitudes poleward of 60˚N monitor aerosol amount and type in seasons when the sun is above the horizon. DOE, NASA, and NOAA aircraft campaigns have also contributed to an integrated understanding of the Arctic atmosphere. The NASA Arctic Research on the Composition of the Troposphere from Aircraft and Satellites (ARCTAS), for example, provided new characterization of bidirectional reflectance distribution functions for aerosols over Arctic surfaces, validated CALIOP lidar aerosol sensing for a range of conditions, and provided detailed characterization of the optical properties of aerosols from boreal fires.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Sustained and improved satellite-observation capabilities focused on SLCFs
- Enhanced in-situ, long-term observations of SLCF's including a methane-observing network
- Improved modeling of SLCF transport and lifetime

Milestones:

- Support process studies and campaigns to validate current satellite retrievals, such as aerosol products from MODIS, MISR, and Visible Infrared Imager Radiometer Suite

(VIIRS) and methane and near-surface ozone from the Tropospheric Emission Spectrometer (TES) on Aura.

- Develop pan-Arctic synthesis of SLCFs from current observations focused on concentrations, sources, and radiative impacts (NASA, NOAA, NSF).
- Develop needs assessment for improved transport-modeling capability (DOE, NSF).
- Support SLCF source identification through transport and regional modeling constrained by satellite and suborbital data.
- Support black-carbon source identification through chemical composition measurement at key observatory locations (NOAA, DOE) and aerosol mapping from space with MODIS and MISR (NASA).
- Support black-carbon radiative impact studies through *in-situ* measurements at key observatory locations and modeling of light scattering, absorption, and aerosol optical depth (NOAA, DOE).
- Develop needs assessment for an Arctic methane-observation network.
- Increase spatial density of Arctic methane measurements.

Science and Technology Gaps and Needs: NASA operates a variety of sensors that monitor trends and transport of SLCF. Satellite retrievals of SLCF's offer poor resolution near the Earth's surface and must be integrated with higher-resolution *in-situ* measurements. Agencies should support field validation campaigns to obtain direct information about aerosol and surface properties as well as other activities that reduce uncertainty in retrievals by satellites.

Large spatial gaps exist in the current network of *in-situ* measurements for SLCF's. Ground-based observatories could make stronger contributions to understanding the role of black carbon by building capacity to monitor the mass concentrations and chemical composition of aerosols in addition to current light-absorbing proxy measurements. Locations should be based on sampling representative air-mass trajectories. Given the spatial extent and diversity of methane sources, a much broader network of sustained methane measurements is required to monitor long-term methane trends, understand the processes that emit methane, and better constrain inverse model studies of the methane budget.

Improve understanding of processes that control the formation, longevity, and physical properties of Arctic clouds, including the effects of, and sensitivities to, aerosols.

Why Do This: Unlike other atmospheric features, clouds and aerosols are unevenly distributed in space and participate in highly integrated processes. Clouds, particularly those at low levels, occur frequently throughout the Arctic. They are particularly susceptible to aerosol influences on both liquid-droplet and ice-crystal nucleation, which impacts cloud formation, persistence, physical properties, and precipitation. Substantial uncertainty surrounds which modes of nucleation are operating under the varying conditions in the Arctic and how they are linked to aerosol composition and sources. Due to regionally unique frequent, low sun angles and high surface albedo, Arctic aerosol and cloud radiative forcing typically have different signs than at lower latitudes. Specifically, they tend to warm the surface predominantly by trapping long-wave radiation more efficiently than they cool the surface by reflecting sunlight. Aerosols can change

cloud cover, thickness, and brightness. These perturbations, thus, have direct implications for the net radiative balance at the Earth's surface and top of the atmosphere. Arctic long-wave radiative forcing from low-laying clouds has been identified as an important control of onset and duration of surface melt, which impacts the mass budgets of sea ice and ice sheets. Additionally, clouds act as the vehicle for precipitation, and, therefore, play a fundamental role in the Arctic hydrological cycle. Due to numerous complex processes involving clouds and aerosols, and a dearth of knowledge on these processes, their misrepresentation in models lead to large uncertainties in climate simulations of (i.e., IPCC AR4). To improve these modeling deficiencies, it is imperative to characterize and understand basic cloud and aerosol properties and their interactions within the system.

U.S. agencies (NASA, DOE, NOAA, NSF) employ satellite, ground-based, and *in-situ* assets to observe Arctic clouds and aerosols. Passive measurements from space are challenging, particularly during winter and over snow and ice surfaces due to low optical and thermal contrast between clouds, aerosols, and the underlying surface. Using satellites to assess the impact of aerosols on Arctic clouds is an even greater challenge for passive remote-sensing instruments due to persistent cloud cover, poor vertical discrimination, bright surfaces, relatively low aerosol column abundances, and low solar-illumination angles, but these measurement limitations are significantly improved by combining passive instruments, such as MODIS (measuring ambient radiation), with active instruments, such as CALIOP and CloudSat (measuring emitted lidar and radar returns). In addition to providing an unparalleled aerosol record going back to 2000, the MODIS and MISR satellite sensors monitor the long-range transport of pollution and smoke into the Arctic.

Important progress has also been made towards understanding cloud-aerosol interactions and properties via aircraft campaigns such as the recent NASA Arctic Research on the Composition of the Troposphere from Aircraft and Satellites (ARCTAS), the DOE Indirect- and Semi-Direct Aerosol Campaign (ISDAC), and the NOAA Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC). For example, ARCTAS provided new characterizations useful for energy balance assessment and a better understanding of aerosol radiative effects, which help to improve satellite measurements. ARCPAC and ISDAC both provided important new perspectives on aerosol composition and transport sources with important implications for cloud processes.

The International Arctic System for Observing the Atmosphere (IASOA) is a pan-Arctic consortium of flagship ground-based observatories supported by NOAA, NSF, DOE, Environment Canada (EC), the Russian Federal Service for Environmental and Hydrometeorolgical Monitoring (*Roshydromet*), the Finnish Meteorological Institute (FMI), and other government and non-government contributors from Arctic and non-Arctic countries. The observatories operate sophisticated instruments that support sustained, high-resolution, and simultaneous observations of clouds, aerosols, atmospheric structure, and the surface-energy balance. These year-round observatories provide excellent platforms for both long-term and campaign-based process studies. DOE's Atmospheric Radiation Measurement (ARM) Climate Research Facility in Barrow, Alaska, for example, provides a long-term record of highly valuable simultaneous measurements of cloud microphysical and macrophysical parameters, aerosols, and surface radiation. Recent additions of scanning radars, powerful lidars, and aerosol instruments

further enhance ARM's measurement capabilities over an extended volume near Barrow. Measurements from that site have been the basis for several successful international model inter-comparison projects focused on cloud-resolving and single-column model simulations, whose goals are to improve Arctic cloud microphysics parameterizations and to better understand indirect effects of aerosols. Instrumentation at the new ARM site at Oliktok, Alaska, mirrors the Barrow site with the added capability of instrumented unmanned aerial vehicles (UAVs). The focus of work at the Oliktok site is to examine clouds and aerosols over land, sea, and ice, as well as the coupled atmosphere-cloud-terrestrial Arctic systems. Ground-based observatories, in general, contribute unique and valuable information for use in model evaluation and development, for validation of satellite observational methods, and for long-term monitoring of Arctic atmospheric properties.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Evaluation, improvement, and development of cloud and aerosol parameterizations in climate and weather prediction models
- Sustained and improved satellite-observation capabilities of cloud and aerosol properties, with verification using surface observations
- Sustained and enhanced ground-based observations including simultaneous measurements of clouds and aerosols
- Improved understanding of how clouds respond to changing levels of aerosols and sea ice
- Synthesis data sets that provide detailed descriptions of clouds and aerosols

Milestones:

- Support sustained and enhanced ground-based measurements of cloud and aerosol properties (DOE, NOAA, NSF).
- Conduct intensive, short-term, ground-based and airborne field experiments to quantify the impact of aerosols on clouds, conduct detailed process studies, and provide validation data sets for remote sensing data (DOE, NASA, NOAA, NSF).
- Support synthesis activities to develop long-term observational cloud and aerosol data sets from ground-based and satellite platforms to evaluate model parameterizations (DOE, NASA, NOAA, NSF).
- Use observational data sets to constrain process-model studies and conduct detailed model inter-comparisons to advance parameterization development (DOE, NSF).
- Support laboratory studies to examine cloud-particle nucleation processes (NSF, DOE).
- Support observations and modeling activities to improve understanding of transport of aerosols from remote regions to the Arctic (NASA, NSF).

Science and Technology Gaps and Needs: The fundamental gap in this topic is represented by the broad difficulties models at many scales have with representing cloud and aerosol processes. This general lack is based upon observational data sets of insufficient length, complexity, and

spatial representation, as well as insufficient process-resolving models. Specific gaps in understanding include processes related to aerosol sources and transport, basic cloud-aerosol interactions, cloud-phase partitioning, the influence of heat and moisture advection on cloud formation, interactions between clouds and atmospheric structure, and the partitioning of precipitation between mechanisms, among others. Enhanced emphasis on observational, laboratory, and model studies is needed in all areas to provide the necessary improvements in model parameterizations.

To address the needs to advance physical parameterizations in numerical climate and weather-prediction models, activities related to cloud-aerosol-radiation processes at DOE, NOAA, NSF, and IASOA observatories should be sustained and enhanced. These measurements should be supplemented by intensive campaigns (NASA, DOE, NOAA, NSF) focused on enhancing ongoing, long-term measurements and targeting specific processes or hypotheses. To expand the spatial footprint of these observations, DOE, NSF, NASA, and NOAA are funding technology development through the Small Business Innovation Research (SBIR) program to enable cloud and aerosol measurements from UAVs and balloon-borne platforms. Enhanced emphasis should also be placed on validation and refinement of satellite measurement technologies for observing aerosol characteristics and transport, as well as characterizing clouds throughout the troposphere (NASA, NOAA). Satellite research would also greatly benefit from international collaboration with European countries and Japan around active measurements from the EarthCare mission and passive measurements from the NPOESS Preparatory Project (NPP) and Joint Polar Satellite System-1 (JPSS-1). Ideally, development of a more advanced satellite-based, multi-angle, multi-spectral, polarimetric imager should be considered. Finally, where appropriate, agencies should support evaluation, utilization, and advancement of smaller-scale process models that can be used in both process studies and as intermediaries for parameterization development.

Develop an integrated understanding of Arctic atmospheric processes, their impact on the surface energy budget, and their linkages with oceanic, terrestrial, and cryospheric systems.

Why Do This: Numerical models are used to understand and predict important processes such as the decline of Arctic sea ice, linkages between Arctic conditions and lower-latitude weather, and the general amplification of climate change in the Arctic. Developing models of sufficient quality, however, relies on building a system-level understanding of Arctic climate that includes detailed knowledge about the Arctic atmosphere and surface and their many interacting processes. Current models face considerable difficulties when representing Arctic atmospheric processes related to boundary layer structure, cloud formation, and aerosol-cloud interactions—all of which interact critically with the surface. Such modeling difficulties result directly from limited, system-level observations, which could be remedied by comprehensive and coordinated measurements of all contributing components. The general inabilities of models to accurately represent the observed decline in Arctic sea ice, for example, and to properly capture its causes represent one tangible example.

Process- and system-level understanding requires coordination and expansion of observational capabilities along with complementary process-modeling activities. Satellite measurements are a

cornerstone of observations as they provide valuable spatial coverage of many key parameters with linkages to those from lower-latitudes. They are often inadequate, however, for quantifying basic parameters such as surface temperatures and providing the level of detail needed for coordinated radiation, cloud, aerosol, and other atmospheric measurements. Additionally, many polar-orbiting satellites take insufficient measurements in the area within 800 kilometers of the North Pole. Although ground-based observations and aircraft campaigns may be spatially and/or temporally limited, they provide the types of measurements needed to characterize many of the necessary processes in high detail. Most existing knowledge on Arctic atmosphere-surface interactions is biased towards land-based or coastal observations and processes. Thus, the challenge is to coordinate existing and new inter-agency observational abilities from satellite, aircraft, and the ground to produce the comprehensive, process-level observations of the Arctic system needed to improve numerical models.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Sustained and improved satellite-observation capabilities focused on atmospheric interactions with the surface and coordination of satellite-measurement capabilities
- Improved understanding of the two-way relationship between sea ice and clouds
- Sustained and enhanced ground-based observations emphasizing simultaneous measurements of clouds, aerosols, atmospheric structure, and surface-energy budget in land- and ocean-based environments
- Improved representation of Arctic systems in climate and weather-prediction models

Milestones:

- Support model-component development and advancement of fundamental knowledge of the key processes that regulate aerosol and cloud impacts on the atmospheric- and surface-energy budgets (DOE, NASA, NOAA, NSF).
- Support research activities that integrate Arctic processes in regional and global models (DOE, NASA, NOAA, NSF).
- Coordinate interdisciplinary campaigns to study the Arctic climate system as a whole (NSF, DOE).
- Explore potential of UAVs for enhanced Arctic observations (DOE, NOAA, NASA).

Science and Technology Gaps and Needs: Three prominent gaps exist in research on Arctic atmospheric processes and their interactions with the broader Arctic climate system: 1) a lack of comprehensive observations at specific locations; 2) a general dearth of process-level observations over sea-ice environments; and 3) limited routine observations in the central Arctic Basin.

Barrow, Alaska, is a primary hub for Arctic research in the United States. Benefiting from substantial observatory and campaign efforts by DOE, NOAA, NASA, and NSF, Barrow likely contains the most comprehensive Arctic atmospheric observatory capabilities worldwide, and in many ways is a model for such observations. This comprehensive level, however, is not currently

available at other key Arctic IASOA observatories operated in Canada, Greenland, Russia, and Northern Europe, often with U. S. support. Efforts should be made to broaden observational capabilities at additional Arctic locations. The new ARM site at Oliktok, Alaska, with instrumentation mirroring the Barrow site—but with the added capability of instrumented UAVs—should attract other agency contributors. Additional instrumentation from other agencies, such as NOAA, NASA and NSF, would provide more-comprehensive observations of clouds and aerosols over land, sea, and ice, as well as the coupled atmosphere-cloud-terrestrial Arctic systems.

The central Arctic Basin represents a substantial spatial coverage gap that limits models of important processes, such as those related to sea-ice decline. Multi-year, detailed, and comprehensive measurements, extending from the ocean through the sea ice and into the atmosphere, are critically needed to provide a process-level understanding of the complex regional systems of interactions and feedbacks that cannot be gained by land- or space-based observations. One option is to establish an intensive, multi-year, surface-based observatory in the central Arctic Basin via an icebreaker-supported ice station. Such an ambitions endeavor will require the coordinated support of multiple U.S. agencies and international partners. The 1997-1998 Surface Heat Budget of the Arctic Ocean campaign (NSF, DOE, NOAA and NASA) was a good example of interagency coordination on a ship-based campaign that provided a first look into many central Arctic processes, but current needs extend well beyond what it provided. Experience from that and other campaigns over the Arctic sea ice has shown that the most valuable data have been obtained from campaigns making comprehensive, multi-disciplinary measurements during one or several annual cycles.

Finally, operational models and model re-analyses assimilate observational data to improve model accuracy. The central Arctic Basin is, however, sparsely populated with routine observational inputs for these models. First, efforts should be made to improve operational satellite products through ground- and aircraft-based validation and algorithm development to provide improved constraints on model performance (NASA, NOAA). Second, expanded operational observations of basic Arctic atmospheric properties are needed, such as those provided by additional radiosonde stations or via routine dropsonde observations. UAVs offer great promise for cost-effective means to make sustained measurements over the central Arctic (NOAA, NASA, DOE). These observational enhancements have the potential to reduce uncertainty in operational models and re-analysis products over both the Arctic and lower latitudes.

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3.4. Integrate and continue to deploy a national Arctic observing system and promote international cooperation to create a circumpolar Arctic observing system.

Lead Authors: Simon Stephenson, NSF; C. Nikoosh Carlo, NSF; Martin O. Jefferies, ONR; and Robert Sanford, NSF

Agency Partners: NSF, NOAA, NASA, DOI, EPA, DOE, ONR, DHS

The Arctic Observing Network (AON) is being developed to provide data parameters key to understanding the changing Arctic environment. Initially a U.S. activity, AON became international during the International Polar Year 2007–2008 and is now endorsed by the Arctic Council. Several documents and reports provide a vision of what an AON should be, as well as recommendations for network design, data approaches, input from local and other stake holders, response to agency specific needs, and international partnerships (see end note). International collaboration has been developed further under the umbrella of the Sustaining Arctic Observing Network (SAON), including participation by the eight Arctic countries, indigenous organizations recognized as permanent participants in the Arctic Council, Arctic Council working groups, and non-Arctic countries and entities (Calder 2011:417–422). The U.S. contribution to the World Maritime Organization (WMO) Global Atmosphere Watch provides another international cooperation mechanism.

For a list of federal observing efforts see, *Arctic Observing Network: Towards a U.S. contribution to Pan-Arctic Observing* (IARPC, 2007).

This section focuses on areas where interagency collaboration will greatly advance Arctic observing priorities. It will not attempt to review ongoing efforts at individual agencies. Suggestions for the general direction of network development are:

1. Agencies should establish key activities or priorities for Arctic research to support their mission. For example, NASA's comprehensive approach uses satellite, aircraft, *in-situ*, and model data to understand the causes of large, rapid changes in Arctic sea ice, glaciers, ice sheets, land surfaces, permafrost, and atmospheric composition and chemistry. Those physical parameters strongly influence health and welfare of citizens throughout the pan-Arctic region, short-term weather patterns over the United States, and global change. NOAA's *Arctic Vision and Strategy* provides accurate, quantitative, daily to decadal predictions to support safe operations and ecosystem stewardship. Both priority areas are also included in the National Ocean Council's Arctic Strategic Action Plan and will benefit greatly from interagency collaboration.

2. Residents of the North—individuals, communities, and their representative governments—need sound information and scientific understanding to make decisions about their future livelihoods, resources, and cultures.

3. Research results should continue to build our understanding of the changing Arctic environment system and contribute to the design of an optimal observing network. From this, new priorities will be added; older ones may decline in importance or change focus.

IARPC plans to focus on nine interagency observing efforts over the next five years. A formal review and update of those priorities will occur every two years as IARPC's five-year plan is refreshed.

Design the Arctic network observation system

Why do this: Long-term observations *in situ*, from space and by local people and communities have been vital to documenting changes occurring throughout the Arctic environment. Without remote-sensing observations from space, for example, the recent dramatic changes in Arctic Ocean sea-ice extent, melting and mass loss in the Greenland ice sheet, and changing tundra "greenness" would not have been detected and quantified quickly. The recognized need for a diverse set of pan-Arctic observations that would improve the value of predictive models spawned the Arctic Observing Network. The Study of Environmental Arctic Change (SEARCH) articulated the need for AON in the first part of the last decade and continues today to refine thinking about the system. More recently, the need was discussed in the National Academy of Sciences report, *Toward an Integrated Arctic Observing Network*.

Progress in understanding the changing Arctic environmental system will be achieved by a variety of methods, including the use of coupled, numerical models that represent a regional Arctic system. Ideally, observations vital to model initialization, calibration, assimilation, and skill-testing are best provided by an optimal network. Optimizing an observing network is a design exercise that itself would employ numerical models to establish observing priorities and identify gaps, optimal observing sites, and observational needs, such as variables to be observed and the frequency and duration of observations. Thus, observing-system design and Arctic-system modeling are symbiotic and require the observing and modeling communities to work together to identify and develop synergies that will improve both approaches. Arctic regional models are discussed in more detail in section 3.5.

Assess local-resident priorities for addressing change.

Why do this: Polar amplification of global environmental change is forcing local Arctic residents to address change immediately and to identify new adaptation strategies while balancing ongoing social, cultural, health, and economic demands and expectations (see sections 3.6 and 3.7). Priorities for the Alaska-Native communities include: human health well-being, subsistence rights, development of alternative energy, and rural dependence on fossil fuels, including predicting how climate change will alter their environment (see Alaska Federation of Natives 2010 and 2011 Federal Priorities, and the Inuit Circumpolar Council Alaska Strategic Plan 2010-2014).

Combine *in-situ* and remotely sensed observations of sea ice with local community and traditional knowledge.

Why do this: The changing seasonality of sea ice will have profound climate, environmental, socio-economic, and political consequences at local, regional, Arctic circumpolar, and global scales. A sea-ice observing system that combines *in-situ* and remotely sensed observations with local community and traditional knowledge can meet the growing need for information about the state of the sea-ice cover at daily, weekly, monthly, seasonal, annual, and decadal temporal scales. As the Arctic Ocean moves toward a more maritime environment, the challenge will be to develop an optimal and integrated sea-ice observing system and derived products that will serve individuals and communities, industry, governments, and scientific research to better understand sea-ice processes and changing seasonality, operational forecasts, and longer-term predictions. Sea-ice processes, interactions, feedbacks, and modeling are discussed in more detail in section 3.1.

Monitor the biological state of the Arctic marine environment.

Why do this: Unprecedented ocean warming and seasonal thinning and retreat of sea ice are altering the biology of the Arctic Ocean, which will potentially lead to ecosystem reorganization. The international Arctic Council has initiated a program to monitor the biological state of the Arctic marine environment. In the United States, a Distributed Biological Observatory (DBO) in the Pacific Arctic sector with emphasis on the Beaufort and Chukchi Seas is envisioned to provide biological and supportive environmental data at explicit regional sites. Portions of the DBO represent the U.S. contribution to the Arctic Council's monitoring program. The DBO would use a collaborative international network of logistical support to track ongoing shifts in ecosystem structure concomitant with climate change. These are discussed more fully in section 3.1.

Continue observation of and research on processes responsible for ice loss, and improve models for accurate projections of future loss.

Why do this: Roughly one-third of the world population lives at or near (within 100 kilometers of) a coastline and will be directly affected by rising sea level.The connection between loss of ice-sheet and glacier mass and sea-level rise is direct and unequivocal; the rate at which the Greenland ice sheet loses mass has increased dramatically in the past decade. These rapid changes result from increased discharge from grounded ice into the ocean and from increased ice melting that far exceed slight increases in surface accumulation. It is therefore unsettling that neither quantitative prediction of future terrestrial ice loss nor credible estimation of an upper limit to future sea level is possible (Solomon et al., 2007). Developing credible estimate of sea-level change and effective mitigation or adaptation strategies requires continued observation primarily from space, as well as research into understanding the processes responsible for ice loss, and modeling improvements that will lead to accurate projections of future land-ice loss.

Assess the effects of atmospheric constituents on surface-radiation balance.

Why do this: While the effects of Arctic warming are easily observed, the energy sources driving those changes are poorly understood. The surface-energy balance—the amount of energy from the sun versus the amount reflected or remitted back into space—is largely unknown due to the unusual effects of clouds and aerosols in polar regions (see section 3.3). The half-year-long polar night, the highly reflective surface of ice, and the unique atmospheric stability allow clouds and aerosols to enhance either warming or cooling depending on conditions. Short-lived climate forcers—which include black-carbon aerosols, ozone and methane—are also thought to enhance Arctic radiative forcing. These and other complex cloud-aerosol processes contribute to some of the largest uncertainties in Arctic regional climate models.

Assess the impact of terrestrial warming and permafrost thawing on the carbon cycle.

Why do this: Recent estimates show that soils of high-latitude ecosystems store about 1,670 picograms of carbon—several orders of magnitude greater than current annual anthropogenic carbon dioxide emissions. Climate-change scenarios predict the greatest magnitude of global warming will occur at high latitudes, and considerable observational evidence indicates recent warmer ground temperatures and permafrost thawing. The size of soil carbon pools and their sensitivity to temperature changes suggests a net loss of old-soil carbon to the atmosphere, causing a positive feedback to climate change. Terrestrial ecosystems are discussed in more detail in section 3.2, and marine ecosystems, including greenhouse-gas fluxes, are discussed in more detail in section 3.1.

Improve data access.

Why do this: The NSF-supported Advanced Cooperative Arctic Data and Information Service (A-CADIS) enables scientific discovery by allowing scientists to easily access, share, integrate, and work with data spanning multiple disciplines. It will provide data to scientists, decision makers, and other stakeholders, including archival services to ensure data accessibility well into the future.

Engage indigenous observers and communities in monitoring environmental parameters.

Why do this: Federal agencies supporting various components of the emerging circumpolar Arctic observation system, both nationally and internationally, will continue to work toward integrating community based observation networks with physical and biogeochemical monitoring systems. Introducing human-focused components to observing and monitoring Arctic change has helped move the AON/SAON network far ahead of previous efforts. The prevailing vision now engages indigenous observers and communities in direct monitoring of various environmental parameters, such as weather, sea ice, coastal erosion, permafrost, marine and riverine resources, and terrestrial wildlife. Resources should be sought to continue community based observation efforts, such as EALAT, BSSN, SIKU and similar projects begun under the

IPY 2007-2008 program. New efforts to convert limited local initiatives into long-term viable programs should be supported by NOAA, FWS, USGS, CG, the Smithsonian, and others.

Timeframe: Long term (>5years) to achieve a sustainable AON; short term (1-3 years) to make substantial progress on several high-priority areas

Expected Outcomes:

- Improved understanding of how the Arctic system is changing and its connections to global systems
- Improved understanding that will allow informed decision making by stakeholders

Milestones:

- Support diverse, multi-disciplinary observing teams that include representatives from state, local, and tribal governments, academia, the private sector, the international Arctic community and other stakeholders (all agencies; AON workshop 2012; AON Summit 2013).
- Assess the state of the nine observing system/network themes and identify knowledge gaps and establish sites or regions for key observations (all agencies, 2013).
- Develop action plans to implement an integrated design, including connections with other national and international observing systems, sustain current and planned operations, and use system models to identify observing contributions and needs for forecasting and design (all US agencies, International observing groups and SAON, 2016).

Science and Technology Gaps and Needs: New activities under this plan should be informed by ongoing efforts at the local, tribal, state, federal, and international levels. Efforts should be made to review existing activities and create synergisms when goals and priorities align. Current research efforts would benefit from advisors from across federal, state, local, and academic research organizations and industry to address AON topics. Such diverse perspectives on high-priority topics could quickly mobilize resources to advance areas of critical need. Current inability to find central key datasets argues for a common portal to assist data discovery. Such a portal should be accessible and intuitive for local community members, educators and the scientific community alike. Better access is needed to radar imagery over sea ice, glaciers, ice caps, ice sheets, and permafrost regions. The ESA Sentinel series and the CSA RADARSAT Constellation will partly fill this gap but will depend on partnerships with overseas operators.

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End notes:

Additional background on AON appears in:

- 2003 *Arctic research Support and Logistics: Strategies and Recommendations for System-scale Studies in a Changing Environment.* ARCUS
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3.5 Integrate Arctic regional models

Lead Author: Mike Kuperberg, DOE

Agency Partners: DOE, DOI, NOAA, NSF

Models of Earth's climate are mathematical tools for understanding climate processes and their feedbacks, as well as for predicting and projecting climate variability and change. A variety of models are being applied in the Arctic region for projecting future climate change, forecasting Arctic weather and sea-ice conditions, and understanding Arctic processes. Yet due to large feedbacks, sparse observations, differences in process representation, and high variability of vegetation, ice, and snow cover, significant uncertainty exists in simulations of Arctic changes. An integrated and focused effort to improve Arctic models would benefit understanding of ongoing processes, ability to project future Arctic changes, and informed use of those projections. Strongly coupling modeling and process-science research ensures that models incorporate state-of-the-science knowledge about critical systems. Process studies can advance understanding in weak or unrepresented areas, and the resulting improved models can be used to guide field research and inform future decisions. The climate community has produced a number of documents that propose research directions; the sections below have made significant use of the Science Plan for Regional Arctic System Modeling (IARC)[1], Modeling and Predicting Arctic Weather and Climate (ICARP II, Science Plan 9)[2], and the Arctic Climate Impact Assessment (ACIA)[3].

Inventory Arctic modeling activities within federal agencies.

Why do this: Significant efforts have been made to coordinate and share research on Arctic regional modeling; however, rapid changes in the pan-Arctic region require broad knowledge about current agency efforts and planned scientific research in Arctic change and modeling. Existing sources and portals that provide a base for comprehensive information and data coordination and sharing include

- National Snow and Ice Data Center (NSIDC), Boulder CO
- The Arctic Portal established as part of the International Polar Year activities and currently maintained by Iceland and various Arctic Council Working Groups
- ARM Climate Research Facility Archive (http://www.archive.arm.gov/armlogin/login.jsp)
- Earth System Grid (http://www.earthsystemgrid.org)
- Polar Hydrography Center, University of Washington
- U.S. National Academies Polar Research Board

[1] Roberts, A. and coauthors 2010. A Science Plan for Regional Arctic System Modeling, A report to the National Science Foundation from the International Arctic Science Community. International Arctic Research Center Technical Papers 10-0001. International Arctic Research Center, University of Alaska Fairbanks.

[2] Bengtsson et al., 2005. Second International Conference on Arctic Research Planning, Science Plan 9, Copenhagen, Denmark. http://www.icarp.dk

[3] ACIA, 2005. Arctic Climate Impact Assessment: Scientific Report. 1042 pp. Cambridge University Press, UK.

- Arctic Ocean Model Intercomparison Project workshops
- NASA Catalog of Earth Science System Components (http://www.asd.ssc.nasa.gov/m2m)
- CESM Polar Climate Working Group (http://www.cesm.ucar.edu/working_groups/Polar)
- NSF's Arctic Long Term Ecological Research (LTER) sites (http://www.lternet.edu/)

Access to and broader use of existing models, data systems, and information portals would better coordinate and integrate existing agency efforts and improve dissemination of data and information about Arctic research activities. An inventory of modeling activities, process research, and data sources would provide a basis for defining collaborative programs and coordinated campaigns for advancing Arctic modeling. Cataloging the existence and nature of activities, such as model inter-comparisons and benchmarking, should be included in such an inventory.

Timeframe: Near term (1-2 years)

Expected Outcomes:

- Collaborative model development efforts and science campaigns
- Greater efficiency through reduction of duplicative efforts

Milestones

- Conduct and disseminate a survey of federal, Arctic modeling efforts.
- Evaluate the results of the survey and identify opportunities for collaborative development and/or joint campaigns.

Science and Technology Gaps and Needs: A comprehensive bibliographic database of results from international entities (such as the International Arctic Science Committee and WCRP's Climate and Cryosphere Program) would provide needed context for how modeling relates to ongoing studies.

Encourage coordinated approaches that better represent Arctic processes in Earth-system models.

Why do this: Global Earth System Models (ESMs) have become increasingly robust, accurate, and comprehensive. Arctic climate differences simulated by ESMs, however, can be large. And many processes are either absent (dynamic ice sheets, ice ecosystems), poorly represented (multi-phase clouds, permafrost, vegetation) or unresolved (ice fracturing, ice shelves, ocean eddies) in Arctic models. Feedbacks in the Arctic are also particularly strong and sensitive; thinning sea ice is very sensitive to both atmosphere and ocean forcing and becomes highly variable with subsequent changes in albedo and other feedbacks; biogeochemical processes that control the rate and nature of carbon release are suspected to lead to dramatic effects on

atmospheric carbon concentrations from thawing permafrost; and ecosystem changes may have direct (albedo) and indirect (ecosystem services) impacts.

Such processes and feedbacks control both regional Arctic and, indirectly, global climate variability. Their realistic representation requires models with very high spatio-temporal resolution as well as detailed and often long-term observations to improve parameterizations and model verification. High-resolution models of Arctic processes will subsequently need to be parameterized and/or scaled for use in current ESMs. International coordination of efforts and cost sharing are important, while maintaining model diversity for more-robust evaluation of a variety of approaches.

Timeframe: Mid-term (3-5 years) for many model improvements already in the pipeline; long term (5-10 years) for next-generation models. The Earth System Modeling Framework (ESMF) or the Earth System Grid (ESG) are currently making models and their output accessible to the larger community but further coordination is needed.

Expected Outcomes:

- Improved inter-agency coordination through dedicated multi-agency campaigns on specific Arctic processes
- Continued development of common modeling frameworks, data and meta-data standards to facilitate increased sharing of model components, simulation, and observational data
- Continued improvement of process representation of the Arctic region in global Earth system models

Milestones:

- Identify critical Arctic processes for dedicated field and modeling campaigns across agencies.
- Coordinate federal activities to develop, implement, and test improved parameterizations of Arctic physical processes and feedbacks.
- Develop standardized model components, meta-data, and data products.
- Conduct model inter-comparisons to foster collaboration between modeling groups and identify high-priority Arctic model improvements
- Review report from the third session of the WMO Executive Council Panel of Experts on Polar Observations, Research, and Services on the development of the Global Integrated Polar Prediction System (NOAA, NSF, FY2012).

Science and Technology Gaps and Needs: While some coordinated efforts exist, such as the AOMIP and Climate Process Teams, they are either volunteer or not sponsored across all relevant agencies. Enhanced mechanisms for interagency collaboration are therefore needed. A variety of Arctic processes lack of observations and process-level understanding for, and modeling frameworks and standards not widely adopted.

Build Arctic and subsystem models for coupling with regional and global approaches.

Why do this: Regional models of the Arctic can more efficiently simulate climate at higher resolution than can Global ESMs and would enable explicit representation of fine-scale atmospheric, oceanic, terrestrial, and cryospheric processes at scales where they occur. Regional Arctic models can also take advantage of the growing number of data streams and process understanding emerging from mechanistic studies and field and laboratory observations and highlight the most critical and sensitive processes and parameters for inclusion in regional and global models.

Regional models are required to fully incorporate the complex interactions between sea ice, ice sheets, cold oceans, regional climate, permafrost stability, and their integrated influence on the regional and global carbon cycle and energy balance. Ultimately, the understanding obtained from these models can be incorporated into global models either through coupling/nesting or by creating appropriate parameterizations. Global Earth System Models will be the primary tool for exploring climate change and the Arctic feedbacks in the global climate system.

Timeframe: Mid- to long term (3-10 years). Focused development of new subsystem models and interaction with experimentalists (>5 years); coupling and evaluation within regional and later in global models (5-10 years).

Expected Outcomes:

- A hierarchy of models from process to regional scales
- Inclusion of Arctic high-resolution physical, biological, chemical, and social subsystem model components within a regional Arctic climate system model
- Improved representation of the Arctic System in Earth System Models through nesting of regional models or development of parameterizations

Milestones:

- Develop and evaluate stand-alone subsystem components of the Arctic System, incorporating mechanistic processes derived from experiments and/or observations.
- Couple, test, and validate the above against observations of subsystem components within a regional Arctic climate-system model.
- Couple and evaluate Arctic subsystem components within global Earth-system models.

Science and Technology Gaps and Needs: Observational data are needed to constrain and rigorously evaluate individual subsystem model components and multi-component interactions and dependencies. Advanced *in-situ* and remote platforms are needed for coordinated process studies, especially for difficult observations such as under-ice sampling and communication, melting out/freezing in, long- time/distance endurance, high-resolution, large-scale, and long-term coverage. Also, community participation in model development and data collection could be better supported by organizational structure as would common, coordinated Arctic data/model distribution center(s) for community posting and use of models.

Increase Arctic model resolution to improve prediction and inform future research and observations.

Why do this: As for many regions across the globe, accurate climate simulations of the Arctic require resolving features and processes at small spatial and temporal scales. Arctic Ocean eddies, cloud processes, ice fracturing, ice-shelf dynamics, ecosystem/vegetation changes, and hydrology all occur on kilometer scales or smaller. Through data synthesis and integration with other models, high-resolution regional models can guide future observations and process studies while providing a large-scale and long-term picture of Arctic climate-system variability. Variable resolution approaches are now being implemented and show great promise for enabling high-resolution Arctic models in a global climate model framework. Similarly, alternative time integration techniques are being explored to capture multiple time scales consistently and accurately.

Process understanding, data sets, and model representations are needed at small spatial and temporal scales. High-resolution model output is also commonly required by stakeholders, especially for impact assessment and mitigation/adaptation studies. While high-resolution global models are beginning to reach these spatial scales, continued use of regional, standalone and nested models will be needed to provide ensemble simulations at the required resolutions. Similarly, fast processes related to surface exchange and boundary layer processes must be represented, as well as decadal modes of variability and longer processes like ice-sheet melting, ecosystem evolution, and ocean thermohaline circulation—all of which have significant impacts on Arctic climate. Results from those simulations can inform process research direction and observing system design (see section 3.4, Arctic Observing Network). Already, high-resolution ocean simulations have been used to help design large-scale ecosystem studies in Arctic permafrost and float experiments in the Southern Ocean.

Timeframe: Mid-term (3-5 years) for improved Arctic climate-system models and variable-resolution models for focused Arctic simulations

Expected Outcomes:

- Improved and detailed forecasts of Arctic climate change to address stakeholders needs
- Arctic simulations at fine-enough resolution to inform experimental/observational design and field campaigns

Milestones:

- Conduct ensemble simulations of future Arctic climate change at kilometer spatial scales.
- Engage the Arctic (and Earth system) modeling community in planning and designing future field campaigns.
- Provide mechanisms for rapid access to processed (quality controlled, formatted / gridded) observational data sets for model-data inter-comparison.

Science and Technology Gaps and Needs: Much of the observational data is not at high enough resolution to validate kilometer-scale models or incorporate into model-data inter-comparisons.

Important gaps in process understanding limit full representation of the Arctic in coupled models. Advanced numerical techniques are needed for multi-scale time integrations. High-performance computing resources and technical support are needed for model integration and enabling co-design of model algorithms and/or new modeling approaches to carry out high-resolution simulations on new computing architectures.

Use insights from models to inform process research; use process research to evaluate and improve models.

Why do this: Analyses of model outputs have frequently produced new insights into Earth-system processes, particularly because models can simulate processes that are poorly understood owing to sparse observations and difficulty in obtaining process data. In that regard, model analyses can highlight the need for additional or new observations and process studies, which will in turn help to improve representation of those processes in models and ultimately benefit predictions about Arctic climate change. While modelers are eager for robust data sets to parameterize and test their products, and experimentalists and observers develop process understanding that can be incorporated into models, the two communities do not often interact directly.

The disconnects among modelers, experimentalists and observers leads to gaps in both the completeness of data for good prediction and in critical process representation in models. Coordinated research efforts are particularly needed in the Arctic where process research is difficult and limited, and where model outputs are highly variable. Great opportunity exists to rapidly improve the design of Arctic experiments and observations, which would enable enhanced parameterization of subsystem, regional, and global models. Such experiments and observations also could identify and address structural uncertainty in models by including coupled experimental and predictive science components to identify gaps and needs simultaneously for both data and models.

Timeframe: Near to long term (1-10 years). Current field research efforts and laboratory process studies are already being informed to some extent by model analyses but more-comprehensive and integrated model and field campaigns will be needed.

Expected Outcomes:

- Improved understanding and model representation of processes specific to the Arctic System
- A new cycle of systems model development and improvement, incorporating integrated field campaigns to develop refined parameterizations for Arctic process representations in models
- More-efficient use of research funds through enhanced collaboration between process researchers, observationalists, theoreticians, and modelers
- Rapid increase in development of robust data sets, process understanding, and improved models and predictive skill

Milestones:

- Analyze model output to determine future needs for data collection and process studies.
- Design and implement integrated modeling and field campaigns focused on specific high-priority processes to improve process understanding and representation in models.
- Develop, test and evaluate new/improved parameterizations.
- Plan and conduct inter- and intra-agency conferences, workshops and campaigns designed to bring process researchers and predictive scientists together to solve Arctic grand challenges.
- Develop funding solicitations that require integrated process-prediction research approach.

Science and Technology Gaps and Needs: Many processes in Arctic systems are not well understood and could be targets for focused research. A partial list includes

1. Ice thickness distribution and ice production due to ice deformations
2. Multi-phase ice, brine channels, melt ponds, and water/brine transport
3. Ice-sheet and ocean interaction, ocean circulation in tidewater fjords, and property exchange over the sill
4. Time-dependent evolution of surface, englacial, and subglacial hydrology for the Greenland ice sheet
5. Ocean circulation and water-mass formation in ice-free Arctic conditions
6. Ocean estuary/fjord subsystem model component for use in climate models
7. Land/submarine permafrost distribution and interaction with atmosphere and/or ocean
8. Permafrost hydrology and changes in morphology and river transport
9. Arctic biogeochemical cycles within permafrost, sea ice, atmosphere, and ocean, including carbon, methane, ice algae, aerosol-cloud interactions, aerosol deposition on ice
10. Arctic mixed-phase clouds and other cloud microphysical processes
11. Surface exchange processes at ice/ocean, ice/atmosphere and ocean/atmosphere boundaries
12. Rates and ranges of change for plants, animals, and ecosystem function
13. Permafrost-soil-vegetation interactions

Integrate Arctic climate-model results with observational validation and verification to understand the principle drivers and uncertainties of Arctic climate changes.

Why do this: Unified, regional Arctic climate-system models are ideal tools to integrate data with understanding across multiple components of the Arctic System. Such models may also be applied to advanced, probabilistic decadal projections. Models must be verified against analytic test cases and reference solutions and validated against the historical record. Ensemble simulations are required to sample the solution space for uncertainty quantification as well as to separate natural or internal modes of variability from externally forced changes.

High-resolution regional model outputs should be critically validated. Such validated models contribute to the optimal synthesis and integration of limited process understanding and

observational data to advance the science of Arctic climate change, including its causality and interdependencies across the Arctic system components. All of these activities are likely to benefit from ongoing and targeted cyberinfrastructure research and tools, such as a collaborative portal, and advanced informatics to analyze multi-scale complexities of macro-regional, and integrated modeling environments.

Timeframe: Mid- to long term (3-10 years)

Expected Outcomes:

- Projection of future Arctic climate change and its impacts with variability estimates
- Determination of key principle drivers of Arctic climate variability and trends
- Integrated comprehensive analyses of causes and effects of Arctic climate change

Milestones:

- Coordinate model experiments and inter-comparisons to critically evaluate regional model results against observations.
- Develop and implement standards for gridded observational data sets.
- Implement a common data portal for both observational data and common model experiments and projections.

Science and Technology Gaps and Needs: Improved diagnostic measures suitable for both observations and model data are needed, as well as statistical techniques for uncertainty quantification. Improved coverage and long-term monitoring of the Arctic will generate better knowledge of present climate and initial conditions for future projections. New techniques for filling in sparse observational data from the historical record will improve model validation. Model improvements and additions should occur as a continuous, iterative cycle. New or enhanced computational and data infrastructure are needed, including improved data archives and distribution, advanced informatics, and access to high-performance computing resources for high-resolution ensemble simulations.

3.6. Assess strengths and vulnerabilities of Arctic communities facing the impacts of climate change, and assist in developing adaptation strategies and tools to maximize sustainability, well-being, and cultural and linguistic heritage.

Lead Authors: William Fitzhugh, SI; C. Nikoosh Carlo, NSF; Igor Krupnik, SI; and James Partain, NOAA

Agency Partners: DOI, DOS, EPA, NSF, NOAA, SI

Rapid Arctic change is forcing residents to adapt to new conditions created by environmental change and diverse socio-economic stressors. Age-old traditional responses, such as diversification of natural-resource harvesting, relocation, and dispersal or concentration in the resource-rich niches, offer valuable lessons, but by themselves may be inadequate to fully address challenges such rapid changes present. New community based participatory research to identify regional and local vulnerabilities and adaptation tools contribute to the growing body of knowledge needed for decision-support science and policy recommendations. Understanding the impacts of climate change could be better served by adding base—or "bottom-up"—assessments of the current drivers of social well-being to computer-generated models and other top-down scenarios used in ecosystem modeling. Focused studies of social indicators of change are underway. *Arctic Social Indicators II* and *Arctic Human Development Report II* will emphasize the key role of local communities in both basic-science discovery and in creating adaption tools that are practical and efficient at the local, regional, and broader circumpolar levels.

Knowledge about thresholds and tipping points, as well as the inherent strengths in the social fiber that affect community resilience would be invaluable in formulating federal-agency policies and in forging collaborations with diverse local stakeholders. The overall scope of new research should be broad and encompassing, but the informative case studies are to be conducted at the community level.

Melding the historic effects of cash and natural-resource-harvesting economies with added stressors associated with modernization and ongoing climate change is challenging but necessary. The emphasis should be to provide Arctic residents with basic scientific knowledge necessary for community leaders to develop sustainable pathways for successful adaptation amid rapid environmental change and a variety of other stressors—while juggling diverse federal, state, and local interests. This is a matter of preserving cultural vitality and improving health and overall well-being for the long term.

In collaboration with local communities, develop methods for assessing community sustainability and resilience and determine the efficacy of current adaptation strategies.

Why do this: Native communities have thrived in the Arctic for millennia, but today's challenges are occurring at a pace faster than ever and may be beyond the capacity of traditional adaptation strategies. There is an urgent need for effective methods to assess community sustainability as northern residents face various socioeconomic challenges, changing local infrastructure needs, and high transportation and living costs. Traditional ecological knowledge should be actively

incorporated in future planning, and more research is needed to identify key indicators of successful adaptation at local and regional scales.

Timeframe: Near-term (3-5 years)

Expected Outcomes:

- Inform new understanding on how climate change, past and present, has been/is being met by Arctic communities and how communities have adapted.
- Improve research and assessment tools for studying the sources of community vulnerability to climate and environmental change and implications for community adaptability developed in partnership with local communities and organizations.

Milestones:

- Identify and develop a database on past and current adaptation strategies used by Arctic communities to combat climate change impacts.
- Determine which strategies have been most successful.
- Document unintended consequences of previous strategies and responses to change.

Science and Technology Gaps and Needs: Limited work has been done to identify what Arctic communities have done, or are currently doing, to adapt to the effects of climate change. Even less is known about the efficacy of those adaptation strategies. Research is needed to, first, identify the suite of climate-change adaptation strategies currently being (or that have been) used, and, second, to analyze the efficacy of those strategies. Particular attention should focus on both community specific strategies and those that were applied more broadly at the regional, national, and circumpolar scales. All research needs to be conducted as joint efforts and in close collaboration with local Arctic communities.

Identify the current vulnerabilities of Arctic communities and ecosystems to climate change and explore their interactions with socio-economic and other stressors.

Why do this: The Arctic is warming faster than any other area on the planet. Climate impacts on Arctic communities occur simultaneously and in conjunction with social and economic stressors, such as high cost of living, infrastructure maintenance, lack of employment opportunities, and shortage of resources for community development (see Section 3.7 for discussion of health-related challenges). These stressors need to be identified and quantified in pragmatic terms. Successful adaptation measures will require attention to multiple stressors as well as close engagement with communities to empower self-sufficiency, initiate smart development, and build adaptive capacity.

Timeframe: Near-term (1-3 years)

Expected Outcomes:

- Assist local communities in better understanding current vulnerabilities to climate change.
- Strengthen or create new partnerships among local stakeholders and resource managers to assess the vulnerability of individual Arctic communities and develop locally based mitigation and adaptation strategies.
- In collaboration with local stakeholders, develop new understanding of how changes in Arctic ecosystems and climate will affect natural-resource harvesting practices.
- Improve public understanding of how the effects of climate change interact with socio-economic stressors in the Arctic.
- Advance engagement of federal agencies with local communities in sharing information on management and use of terrestrial and marine resources, and support empowerment for the co-creation of knowledge.

Milestones:

- Establish research and community collaborations aligned with local priorities and needs, including in planning, data collection, conceptualization, and interpretation of research results and recommendations.
- Assess vulnerability of Arctic communities and ecosystems to climate change and socio-economic stressors (BOEMRE's ESP Indicators Study; USGS; NSF's Arctic Sustainability initiative).
- Develop a standardized set of quantifiable socio-economic indicators of vulnerability ("Baffrey Proposal" on Indicators to AC; ESP Indicators Study; Arctic Social Indicators Study).
- Create community profiles that highlight impending vulnerabilities and indicators of resilience (GAO Report i.e. GAO-04-142 and GAO-09-551; USGS Studies; USACE study; UAF Sea Grant Program studies).

Science and Technology Gaps and Needs: Research on the vulnerabilities and indicators of resilience of individual Arctic communities to climate change is limited. Thus, there is a need to develop quantitative measures of vulnerability and resilience to climate change for coastal communities, which can be compared with concurrent socioeconomic stressors. More-objective analysis will improve the content and quality of socioeconomic-impact assessments associated with policy actions and marine resource-management decisions. Such research will enable affected communities to develop strategies for best responding to the challenges and opportunities they face.

Develop projections of future climate scenarios and demographic conditions to forecast potential strengths and weaknesses of human and ecological systems in the Arctic.

Why do this: Given current global environmental changes, the future will not be like the past; scenarios of future conditions help define alternate projections of environmental and socioeconomic states and—with identified uncertainties—will be valuable to adaptation planning.

Timeframe: Long-term (>5 years)

Expected Outcomes:

- Improved models that allow communities and resource managers to better assess potential community and ecosystem-level vulnerabilities to medium- and long-term climate scenarios as well as the relative benefit of specific actions to address those vulnerabilities at the decadal scale

Milestones:

- Develop a standardized set of socio-economic indicators to measure future community resilience (2020 and 2030 projections), including input of local resources, population fluctuations and migration, communication networks, and capacity to adapt.
- Link climate models with projections of ecological and socio-economic change that include community dependence on harvesting local food sources.

Science and Technology Gaps and Needs: Knowledge is lacking about how climate change might disproportionately impact communities and the ecosystems that they depend on for survival. A comprehensive research plan needs to be developed to collect the suite of information needed to model forecasted impacts. Once such models are created, adaptation strategies that respond to those impacts can be developed with local communities and various state and federal agencies that can aid in moving explicit goals forward.

Assist Arctic communities in documenting, revitalizing, and strengthening indigenous languages and cultural heritage.

Why do this: Arctic communities have long faced threats to their indigenous languages and cultural continuity, most recently due to new technologies, communication, education, and digital media. At the same time, the digital era offers new channels for distant education, online publication, and broad dissemination of cultural materials. It is also creating new challenges, as most traditional cultural, subsistence, and language skills are still being transmitted by direct contact within families and communities. The impact of these and other new forces on the Arctic's indigenous people is poorly understood. Federal institutions need to develop a unified strategy or policy for assisting Arctic residents with 21st century challenges to their cultural well-being. Many communities are eager to address the progressive loss of traditional knowledge and language and are willing to work in partnership with federal and local agencies to develop new strategies to preserve and use their unique cultural heritage.

Timeframe: Mid-term (3-5 years)

Expected Outcomes:

- Assess the existing federal and state resources that support Arctic people's cultural heritage and ways to expand collaboration with indigenous communities in language, knowledge, and heritage preservation.
- Aid local users—local programs, cultural institutions, schools, branches of local governments and communities—in developing policy recommendations to both federal and state agencies for collaborative actions in support of indigenous cultural heritage, languages, and identities.
- With local communities develop new programs and templates for cultural preservation, including language revitalization.

Milestones:

- In concert with local communities, strengthen partnerships between researchers, Alaska-Native organizations, federal, state, and NGO entities through strategic projects, workshops, and conferences (Alaska Science Conference, NPS Beringia Days, and SI Inuit Studies Conference).
- Develop tools that Arctic communities can use to more effectively support indigenous languages, traditional ecological knowledge, and natural resource harvesting activities (SI, NSF and NEH endangered language programs).
- Create community profiles that highlight continuity of indigenous languages and knowledge systems (DoEd, NSF, NEH; Alaska state offices).
- Identify and strengthen federal, state, and local efforts related to indigenous languages, traditional knowledge, and cultural heritage.
- Develop research programs to monitor the status of indigenous languages and knowledge systems and to better understand factors affecting language and cultural resilience (NSF, NEH, Smithsonian, in coordination with Alaska state agencies and academic researchers).
- Share and publicize best practices in community efforts to preserve indigenous cultures and languages.

Science and Technology Current Gaps and Needs: Arctic communities have been and will continue to adapt to new technologies, communication, and preservation tools to sustain their cultures and languages. The strengths and threats from the new electronic and media era to indigenous languages has not been adequately studied, nor is a reliable assessment of the opportunities offered by new technologies available to guide federal and state policies. Digital technologies are being increasingly used in support of indigenous languages and knowledge systems, but many critical issues, such as data management, data sharing, compatibility, and local resources remain unresolved. Research is needed to identify key components necessary for the application of new digital technologies and for collaboration of the many players at the federal, state, local, and community levels.

3.7. Understand factors that impact human health in the Arctic, including infectious and non-communicable diseases, climate change, environmental contamination, and behavior and mental-health disorders.

Lead Authors: Alan Parkinson, CDC; and Marya Levintova, NIH

Agencies Partners: CDC, EPA, IHS, NIH, USARC

Although health and survival of Arctic indigenous peoples have improved over the past 50 years, disparities remain between such indicators as life expectancy, infant mortality, and leading causes of death when compared with their respective national populations. Life expectancy of the indigenous peoples of Alaska, northern Canada, and Greenland is lower than that of the general populations of the United States, Canada, and Nordic countries. Similarly, infant mortality among indigenous segments of those populations is higher than that of the comparable national populations. Meanwhile, mortality rates for heart disease and cancer—once much lower among the indigenous populations of the United States, Canada, and northern European countries—now mirror their respective national rates. In addition, indigenous populations of Alaska, Canada, and Greenland have higher mortality rates for unintentional injury and suicide. Other health concerns of those groups include a high prevalence of infectious diseases such as hepatitis B and C, *Helicobacter pylori*, infant respiratory syncytial virus (RSV), tuberculosis, and sexually transmitted diseases, as well as heath impacts associated with exposures to environmental pollutants, rapid economic change and modernization, and climate change (Young & Bjerregaard, 2008).

The majority of DHHS-supported research in the Arctic is carried out within Alaska in collaboration with scientists at the University of Alaska, the State of Alaska, and the Alaska Native Tribal Health Consortium (ANTHC). Most activities are funded by individual NIH institutes and/or CDC centers; however, some activities receive support from non-DHHS agencies, such as the EPA and U.S. Arctic Research Commission. The CDC maintains the Arctic Investigations Program, which is a field station located on the ANTHC campus in Anchorage. AIP provides a platform for collaborative biomedical and prevention research focused on improving the health of Alaska Native population and promotes circumpolar health through linkages with CDC centers, the International Union for Circumpolar Health, and the Arctic Council's Sustainable Development Working Group's Arctic Human Health Experts Group (Parkinson 2010). CDC also maintains the Alaska Pacific Regional Office of the National Institute for Occupational Safety and Health, which conducts occupational safety research to reduce hazards in the Arctic.

Supporting further multi-agency research will contribute to knowledge of factors affecting human health in the Arctic, and lead to development and implementation of prevention and control strategies that will greatly improve the health and well-being of Arctic residents.

Continue and expand circumpolar surveillance of and research on infectious and non-communicable diseases, trauma, and injuries.

*Why do this:*The International Circumpolar Surveillance (ICS) of Emerging Infectious Diseases was established in 2000 as an Arctic Council Sustainable Development Working Group project. Effective surveillance can facilitate timely control of outbreaks, inform public health officials' decisions on research and resource allocation, and provide data to maximize prevention and control strategies. Population-based surveillance of diseases of concern is conducted by public-health agencies in the United States, Canada, Greenland, Iceland, Norway, Finland, Sweden, and the Russian Federation. Linkage of those systems has created a network of hospitals, public-health agencies, and reference laboratories throughout the Arctic to collect, compare, and share uniform laboratory, epidemiological, and research data on infectious diseases and assist in forming prevention and control strategies (Parkinson et al., 2008).

Cancer research depends upon population-based cancer registries for monitoring cancer burden, which can be assessed in terms of mortality, incidence, health-care use, and economic cost. Planning and evaluating cancer screening programs depend upon disease-stage and incidence data provided by population-based registries. At NIH, the National Cancer Institute has supported the Alaska Native Tumor Registry since 1999 as part of its Surveillance, Epidemiology and End Results (SEER) Program. Data from SEER show that gastric cancer is the third most-common type of cancer in the Alaska Native population (Wiggins CL 2008). Commonly associated with *Helicobacter pylori* infection, the mortality rate for gastric cancer in the Alaska Native people is more than three times that found in the general U.S. population (Miernyk et al., 2011). More research is needed to determine the linkage between *Helicobacter pylori* infection and gastric cancer and peptic ulcer disease in Alaska Natives and other indigenous Arctic populations. In addition, there is an urgent need for effective strategies for treating *Helicobacter pylori* in Arctic populations where infection is endemic. Hepatitis B virus infections occur at endemic rates in Arctic populations and result in high rates of long-term problem such as cirrhosis and cancer of the liver. However, more needs to be learned about the prevalence and clinical impact of hepatitis C (Young and Bjerregaard 2008).

Native people living in Southwest Alaska suffer a high burden of acute and chronic respiratory disease. For example, one in four infants from the region is hospitalized annually with acute respiratory infections. Hospitalization rates of respiratory syncytial virus (RSV) infection in infants are the highest documented (Karron et al. 1999). Bronchiectasis, a chronic lung aftermath of severe pneumonias, is common among Alaska Natives in that region (Singleton et al. 2000). A combination of substandard housing, overcrowding, poor indoor-air quality, lack of indoor plumbing, and other environmental factors contribute to such conditions (Hennessy et al. 2008). Alaska rates last among U.S. states for adequate sanitation service; approximately 23 percent of rural Alaskan households lack in-home water and sewer service. Hospitalization rates for respiratory, skin and invasive-bacterial infections are all higher among persons living without running water. Research is needed to reduce environmental triggers of respiratory disease in homes and develop strategies to address the ongoing disparities in sanitation services and the resultant health impacts.

Problems resulting from trauma and injuries are among the most serious that affect people living and working in the Arctic. Injuries are by far the most important causes of death among people around 35 years of age there (Young and Bjerregaard 2008). While unintentional injuries have always been a hazard of living and working in the Arctic, sociocultural changes and the general

availability of alcohol have changed their pattern and extent. Alaska also continues to have a high work-related fatality rate, mostly from drownings in the commercial fishing industry and plane crashes in aviation, which are exacerbated by the cold and remote and Alaska climate. More research is needed to understand the causes and potential interventions needed to reduce the morbidity and mortality associated with intentional (suicide) and unintentional injuries. Special attention should continue to be given to preventing drownings and aircraft crashes. Worker health and safety in oil-spill response in the Arctic or other ice-covered waters poses new concerns as interest in natural resource exploration and extraction increase.

Timeframe: Long-term (5-10 years)

Expected Outcomes:

- The circumpolar surveillance of invasive bacterial diseases (causes of pneumonia, meningitis, septicemia) is ongoing and will be used to monitor the impact of intervention programs as they are implemented.
- Together with the Public Health Agency of Canada, ICS will expand to include surveillance of tuberculosis in the U.S. Arctic, northern Canada, Greenland, and six northern regions of the Russian Federation for the collaborative systematic collection, interpretation, and dissemination of information pertaining to tuberculosis in circumpolar populations for use in epidemiologic study, policy generation, program design, and evaluation.
- Use of cancer registry data will allow planning and evaluation of cancer-screening programs and will contribute to the reduction in cancer incidence and mortality.
- Develop consensus guidelines for the diagnosis and treatment of *Helicobacter pylori* in Arctic populations, and undertake a circumpolar study on putative bacterial markers of virulence and host and environmental risk factors associated with peptic ulcer disease and gastric cancer in Arctic indigenous peoples. Potential markers will be validated in a prospective study of gastric cancer patients and matched controls to identify persons at risk for early screening.
- Promote and collaborate on surveillance research and management programs of chronic hepatitis B and C using patient registries, increase screening and vaccination for hepatitis B in Arctic, and design collaborative research programs on virology and pathogenesis of hepatitis B and C in the Arctic.
- A North American Free Trade Agreement funded project will measure air quality and implement home-based intervention strategies to reduce levels of home-based environmental triggers of respiratory disease. Additionally, this project will measure the impact of these interventions on the severity and frequency of respiratory symptoms in Alaska-Native children with respiratory disease and their families.
- Improve the water and sanitation services available to rural Alaskans by bringing together various stakeholders to determine strategies to address the ongoing disparities in sanitation services and resultant health impacts.
- Continued development of strategies to prevent morbidity and mortality among workers in Alaska is needed particularly in the commercial fishing and aviation industries.

- A retrospective study of all Arctic maritime disasters and oil spill is being conducted, which will provide detailed information about casualties sustained during those events as well as hazardous exposures suffered by responders, including search and rescue and spill clean-up personnel. The results of this project may be incorporated into U.S. oil-spill contingency plans and could be adopted as an addendum to the revised spill response plan being developed by EPPR and/or used as source material for occupational safety and health insertions in that plan.
- Develop strategies to prevent morbidity and mortality among oil spill response workers in the Arctic environment. Results may be incorporated into U.S. oil-spill contingency plans, and could be adopted as an addendum to the revised spill response plan being developed by EPPR and/or used as source material for occupational safety and health insertions in that plan.

Milestones:

- Publish a comprehensive report on Circumpolar Surveillance of Infectious Diseases for the Arctic Council Ministerial (CDC, FY2013).
- Conduct 5 year retrospective review of tuberculosis in northern Canada, the US Arctic, Greenland and northern regions of the Russian Federation (CDC, FY2013).
- Maintain Alaska's compliance with standards of the National Program of Cancer registries and the National Association of Central Cancer Registries (CDC, FY2012).
- Draft and publish a *Helicobacter pylori* treatment consensus document for high-prevalence. Validate *Helicobacter pylori* bacterial markers of virulence and host and environmental risk factors associated with peptic ulcer disease and gastric cancer in Arctic indigenous peoples (CDC, FY2013).
- Increase screening and vaccination for hepatitis B in Arctic and the design collaborative research programs on virology and pathogenesis of hepatitis B and C in the Arctic (CDC, FY2012).
- Measure indoor air quality before and after home-based intervention strategies in homes of children with chronic respiratory diseases. Measure severity and frequency of respiratory symptoms in children before and after the interventions (CDC, IHS, FY2012-2013).
- Conduct stake holder meetings to address scientific, technological, and policy challenges associated with lack of sanitation services in Alaska. Conduct scientific activities to determine health and economic consequences associated with lack of sanitation services in Alaska using epidemiologic studies and economic models (CDC, USARC, FY2012-2013).
- In collaboration with other Arctic nations, publish a supplement to the Arctic Council's *Field Guide for Oil Spill Response in Arctic Waters*, which will contribute understanding and control of the unique hazards that exist to workers responding to an oil spill in the Arctic (CDC, NIOSH, FY2013).
- Maintain the Alaska Occupational Injury Surveillance System in cooperation with the State of Alaska. Publish 20 years of occupational safety research to document progress and set goals for the next 10 years (CDC, NIOSH, FY2013-2014).
- Continue work with the USCG and Native Community Development Groups to identify ways to encourage the use of personal flotation devices and personal locator

beacons while commercial fishing. Continue partnerships with marine-safety educators to provide cold-water survival classes in remote native villages (CDC, NIOSH, FY2012-2014).

- Conduct focus groups with pilots and company owners flying to remote villages to identify strategies to combat pilot fatigue, particularly in the high-risk summer months (CDC , NIOSH, FY2101-2013).

Science and Technology Gaps and Needs: Lack of sufficient numbers of certified Tumor Registrars has impeded the technological progress of the Alaska Cancer Registry. The absence of electronic means for hospitals and physicians to report to the central cancer registry is a technological gap. Further technological advances are needed to provide in-home sanitation services in Arctic environments. Challenges include improving energy efficiency of water systems operations; alternative delivery and waste-removal technologies that address specific problems posed by the climatic, soil, and permafrost; and changing source-water parameters. Technology that provides adequate volumes of water to maximize health behaviors balanced against water and energy conservation is needed.

Continue interagency collaboration to monitor the impacts of climate change and environmental contaminants on human health.

Why do this: Average winter temperatures in the Interior, Arctic Slope, and Northwest Alaska have warmed considerably (~4 degrees C) since the mid-1970s, resulting in extensive glacier melting, thawing permafrost, reduction in Arctic Ocean sea-ice extent, precipitation increases, decrease in duration of snow cover, longer ice-free seasons on lakes, altered food webs, and greater risk of wildfires. Warmer temperatures may cause environmental contaminants to move more readily from soil and water to air; a greater movement of contaminants from lower-latitude source-area soils (industrial sites, agricultural areas, etc.) with greater deposition in Arctic regions; and contamination of traditional foods with man-made chemicals such as polychlorinated biphenyls (PCBs), dioxins, toxophenes, and other pesticides. In the Arctic, those chemicals may be enriched in the marine- and land-based food webs and end up in humans. These compounds are possibly associated with adverse health outcomes and have caused some Alaska Natives to decrease consumption of traditional marine subsistence species and substitute with less-healthy western foods (ACIA 2005).

The impact of climate change on communities includes the disruption of permafrost-dependent structures, threats to village water supplies and sanitation systems, reduction in availability of subsistence species, and decreased air quality (wildfire smoke, dust and pollens). Health threats from climate change include morbidity and mortality resulting from trauma and injury associated with extreme events (storms, floods, increased heat and cold) and unpredictable ice conditions, increased mental and social stress related to changes in environment and loss of traditional lifestyle, decreased access to quality water and food sources, and potential changes in prevalence of some parasitic and zoonotic infectious diseases (Parkinson 2008). Evidence also exists for health consequences from exposure to toxic metals, such as mercury and lead. There may be adverse effects from exposure to organochlorines and mercury on child neuropsychological development and of organochlorines on their immune function and susceptibility to infection.

New and previously experimental or seasonal shipping lanes are being opened in the Arctic as sea ice retreats, and oil and mineral exploration markedly increase. These transport and industrial activities raise the possibility of increasing numbers of shipping disasters and oil spills, with increased risk to human workers, as well as to the marine environment, fauna, and flora. The EPPR Worker Hazard Reduction Project will attempt to address some of those emerging hazards.

Consequently, there is need for studies that collect and analyze human-health and ecosystem observations in rural communities located in the many diverse and ecologically-distinct areas of Alaska. In addition, studies that quantify the cumulative health effects of exposure in Alaska Native mothers and their infants to multiple environmental contaminants (anthropogenic POPs and mercury) in subsistence foods (salmon) is needed.

Timeframe: Mid-term (3-5 years)

Outcomes:

- Community health assessments are designed to assess, one village at a time, the existing and emerging threats and to provide residents with the training and capacity to monitor existing threats, detect new threats, and allow the development of adaptation strategies. The village-based monitoring programs conducted by ANTHC will form a network that contributes data to state and federal agencies to better inform those programs responsible for both human and wildlife health. The outcome of these programs could link with developing programs in Canadian Arctic communities.
- Engaging Alaskans as lay observers of human health and ecological events potentially associated with climate change can provide the public-health community with an important early warning of public-health consequences from such change. This University of Alaska, Anchorage project will provide public-health professionals and other decision makers with a network for the dissemination of informed and culturally appropriate risk communications to guide adaptation planning that reduces health impacts on the Alaskan population.
- A data base of organochlorines, toxic metals, and micronutrients levels in human and salmon tissue will allow the detection of any associations between prenatal exposure to organochlorines and/or mercury with adverse health outcomes, as well as any positive associations between micronutrients levels and health. A time series in human- and subsistence-species tissue levels of organochlorines and mercury will help evaluate the impact of climate regime change on ocean and atmospheric current delivery of those toxins from lower latitudes into the Bering Sea, addressing possible climate-change impact on subsistence resources and human health. ANTHC will provide and communicate risk and benefit data to Alaska Natives to enable region-wide strategies and policies to reduce the risk, and increase benefits of the traditional diet, which will strengthen that critical component of Alaska Native culture.
- Evaluate climate-sensitive infectious-disease surveillance systems for—and baseline levels of infection in—humans and wildlife in Alaska. This will result in better understanding of the epidemiology and risk to subsistence wildlife species and to the

people who depend of them for food, allowing for rapid detection of outbreaks and development of prevention and control strategies.

Milestones:

- Conduct community health assessments and initiate training and deployment of monitoring technology. Develop a web-based monitoring network and village adaptation strategies, and establish the monitoring database. Conduct statistical analysis of laboratory specimens and share data with agencies and jurisdictions. Provide feedback to tribal leaders. Continue planning with interested agencies to develop support for ongoing monitoring and extension to interested communities in Alaska. Disseminate program results to other circumpolar communities and affected communities in the lower 48 states (IHS, FY2012-2015).
- Develop, deploy, and assess a surveillance and response Toolkit for Alaska to promote community based adaptation planning for climate change. Deliverables will include training protocols, a web portal, a surveillance dataset organized by region, adaptation and mitigation recommendations, and reports/manuscripts for peer-reviewed publication (CDC, FY2012-2013).
- Recruit a cohort of 200 Alaska Native women for collection of blood samples, patient interview, and medical-chart information. Collect and chemically analyze salmon tissue samples (DOI, EPA, CDC, FY2012-2015).
- Conduct surveillance evaluations and sero-prevalence studies on humans and wildlife for potentially climate-sensitive infectious diseases such as those caused by *brucella*, *trichinella*, *echinococcus*, *toxoplasma*, *francisella*, *giardia*, and *cryptospordium* species (CDC, DOI, FY2012-2013).
- Implement a NOAA-CDC memorandum of agreement for environmental and public health impacts providing exchange of scientific expertise and resources in the areas of climate, weather, water, and environmental, oceanographic, and atmospheric health as it relates to public health (DOC, CDC FY2012-2015).

Science and Technology Gaps and Needs: Findings from community assessments will require engineering solutions to be developed and applied by the ANTHC Division of Environmental Health and Engineering. Technology will need to be developed for ongoing village-based surveillance and determining seroprevalence of zoonoses in killed subsistence animals, as well as village-operated sampling for climate-sensitive microbial threats to water security, such as *giardia*, *cryptosporidium*, *toxoplasma*, *tularemia* and harmful algal blooms. Development of filter-paper blood-spot tests of animal blood are needed to monitor zoonotic diseases and possible contaminants. There is a general need to improve laboratory diagnostics and molecular-typing systems for many potentially climate-sensitive parasitic and zoonotic infectious agents in humans in wildlife. Finally, adaptation and mitigation planning may require local, state, and national coordination to conduct and evaluate further surveillance measures.

Continue to support investigator-initiated research in major health-priority areas.

Why do this: NIH, the leading U.S. biomedical- and behavioral-research agency, budgeted some $34 million dollars to support more than 80 research projects in the Arctic from 2009-2012. These projects are conducted by investigators at individual institutions with many having multiple research partners. NIH funding is awarded primarily to research and related institutions in Alaska and the Arctic, to non-Alaska institutions focused on indigenous populations, and to increase biomedical research capacity among native and non-native Alaska populations.

The University of Alaska Center for Biomedical Research Excellence (COBRE) program at the Center for Alaska Native Health Research (CANHR) and the Alaska *Institutional Development Award for Biomedical Research Excellence* (INBRE) program receive the largest proportion of NIH funds in the region. Both programs are funded through the National Center for Research Resources to support studies of chemical agents (especially contaminants in subsistence foods) and zoonotic and vector-borne microbial agents of disease. CANHR projects represent one example of multi-agency involvement that includes tribal and local communities, CDC, IHS, and other organizations.

NIH-supported projects in the Arctic also focus on behavioral and mental-health problems, including addiction and related disorders. The National Center for Minority Health and Disparities (NCMHD) and the National Institute on Drug Abuse have supported dozens of research projects on the determinants of substance abuse and mental health disorders in the Arctic. Additionally, NCMHD supports studies of various interventions for substance abuse and mental illness in Alaska.

In addition, NIH has engaged with USARC, CDC, the State of Alaska, and local and academic institutions to develop priorities for research increases in Alaska, particularly on health-care delivery innovations, including telemedicine and information technology**.** The results of a workshop convened by those entities in Alaska indicate there is major need for better communications between and among agencies in and outside of Alaska on issues related to health research, and that there is need for inclusion of local communities or tribal groups in research planning and implementation. Inclusion of innovative and culturally appropriate methods of study is also needed (Levintova et al 2010).

Timeframe: Long-term (5-10 years)

Outcomes:

- NIH will continue to support investigator-initiated, peer-reviewed research projects in biomedical and behavioral sciences in the Arctic. Many NIH-awarded projects engage multiple partners.

Science and Technology Gaps and Needs: As need for further funding of biomedical and behavioral research in the Arctic continues, NIH will support appropriate investigator-initiated, peer-reviewed projects. However, a number of gaps should be highlighted:

1. Alaska-based institutions and researchers have not historically been highly competitive in peer review. This gap may be filled by developing collaborations with NIH-funded

researchers in the lower 48 who are interested in conducting biomedical and behavioral research in Alaska. Furthermore, programs such as INBRE and COBRE present opportunities to build capacity at Alaska institutions that receive less NIH funding.

2. It is difficult to recruit from the sparsely populated native villages in Alaska the large numbers of participants needed to conduct longitudinal studies of chronic diseases. Genetic and cultural similarities among Arctic native populations would allow for statistically meaningful cohorts if communication and information exchange among researchers were optimal.
3. Finally, in addition to large population-based studies, exploration of alternative research design (such as small sample design and studies in low-resource settings) is needed.

Continue to engage indigenous communities and tribal groups in research activities and projects in the Arctic.

Why do this: Indigenous community members and their leaders should be involved in all stages of the research process—from formulating projects and methods, through determining research outcomes, to interpreting and disseminating results. Genuine collaboration between researchers and indigenous communities entails partnerships that value mutual trust and cooperation. Optimal community-researcher relationships share power and resources that enable culturally sensitive research with shared benefits.

Timeframe: Long-term (5-10 years)

Outcomes:

- NIH and CDC-supported investigators, and others, interested in conducting research in the Arctic/Alaska work closely with community and tribal organizations/leaders in developing and conducting their research. In many cases, projects require tribal permission to be carried out in the community.
- National Heart Lung and Blood Institute provided funding to the Norton Sound Health Corporation, a native-owned health corporation, as one of three grantees to conduct the second phase of the Genetics of Coronary Artery Disease in Alaska Natives study.

Milestones:

- NIH and CDC supports research through CANHR where researchers collaborate with tribal and local communities on a number research topics, including nutrition, alcohol consumption and abuse prevention, drug abuse and prevention, and others.

Science and Technology Gaps and Needs: Better communication and more information exchanges are necessary between the researchers and the community before the start of research, during, and after its completion.

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Research Infrastructure

Because the Arctic is geographically remote and environmentally harsh, advancing regional knowledge requires specialized research platforms and instruments. Needed infrastructure ranges from direct on-the-ground observations to satellite observations with advanced instruments. National and international assets are regularly brought to bear; that infrastructure, its use, and availability are summarized in Table 1. When feasible, international coordination of infrastructure and cost sharing is highly desirable.

Satellite instruments are especially powerful tools for observing the remote Arctic. NASA and its partners, especially NOAA and the agencies' funded academic institutions, operate nearly 300 airborne instruments, most of which collect data from the Arctic. Reliance on foreign satellites for some observations and measurements is also now common. Instruments most critical to this plan are listed in Table 1.

The full list can be viewed at http://airbornescience.nasa.gov/instrument/all.

Similarly, NASA and its partners, including some commercial entities, operate nearly 60 research aircraft, many of which apply to Arctic work. The aircraft most critical to this plan are listed in Table 1.

The full list is at http://airbornescience.nasa.gov/aircraft.

Arctic Ocean research employs ice-breaking or ice-strengthened vessels, which are operated by the Coast Guard, the University-National Oceanographic Laboratory System (UNOLS), NOAA, private contractors, and foreign governments. As sea-ice cover in the Arctic Ocean diminishes and vessel traffic increases, national needs for Arctic vessels for research, national security, and marine safety are being assessed. Other important platforms for Arctic oceanographic studies include instrumented moorings, autonomous vehicles, aircraft, and sea-ice camps.

On land, field stations are especially useful for long-term observations and for supporting shorter-term field camps, as are satellite and aircraft-borne instruments.

Electronic media and distribution systems are critical to data acquisition, transmission, and archiving and to communicate research results to the greater scientific community and public. As data on Arctic systems has become more voluminous, the need for more-sophisticated systems, standards, and sharing agreements has increased.

Table 1. Infrastructure needed to accomplish the five-year Arctic research plan. For each infrastructure element, its use, availability, and relevant sections of the plan are identified.

INFRASTRUCTURE	USE	AVAILABILITY	SECTION
Space-based			
NOAA Satellite missions	Weather and key climate variables	Available through 2017	3.1-3.4
Defense Mapping Satellite Program	Mapping sea ice with passive microwave	Available through 2017	3.1-3.4
NASA Earth Observing Satellites	Detailed studies of sea ice, clouds, and other Arctic parameters	Many are past design life	3.1-3.4
National Polar-orbiting Operational Environmental Satellite System	Next generation weather satellite	SUOMI has planned operational life to 2017; other satellites are in planning stages	3.1-3.4
LandSat Data Continuity Mission	Land cover change	Launch in 2013	3.2
Global Precipitation Measurement	Measure snowfall and heavy rain	Launch in 2014; Limited footprint over polar regions	3.3
GRACE follow-on	Arctic oceanography, changes in ice mass, terrestrial water storage	Launch in 2014	3.1-3.4
SMAP	Soil moisture, freeze thaw patterns, and potentially sea ice mapping	Launch in 2015	3.1-3.4
ICESat 2	Altimetry over land and sea ice to measure changes in thickness	Launch in 2015	3.1-3.4
CryoSat 2 (ESA)	Sea ice thickness	Planned mission duration: 2013	
SARS (Synthetic aperture radar; e.g. Canada's Radarsat; Germany's TerraSAR)	Measure ice motion	Likely through 2017, but data must be purchased	

OceanSat 2 (India)	Ocean wind speed, sea ice roughness and thickness	Likely exceeds design-life before 2017	
Airborne Instruments			
LIDAR altimetry. NASA Goddard builds ice and vegetation mapping lidars that operate at both low and high altitudes, on piloted and UAS aircraft. Commercial lidars are available for smaller scale work.	LIDAR is used to map sea ice thickness and changes in ice surface heights over land based ice.	Available through 2017	3.1, 3.4
Radar. NASA and NSF support various institutions that develop and operate snow and ice radars.	Snow thickness over sea ice, bed maps under land ice, structure of land ice.	Available through 2017	3.1, 3.4
Aircraft			
P-3 (NASA)	Land ice and sea ice	Available through 2017	3.1, 3.4
DC-8 (NASA)	Atmospheric, land-ice and sea ice	Available until 2014, when the aircraft requires major refurbishment	3.1, 3.3, 3.4
Global Hawk (NASA)	Atmospheric measurements from high altitude (65,000 feet)	Available through 2017. Two aircraft are operational for research, others could be made available	3.1, 3.3, 3.4
Ikhana (NASA)	Sea ice and oceanographic measurements, including buoy drop capability	In development for availability in 2013	3.1, 3.4
C130 (USCG)	Sea ice awareness	Available through 2017	

LC130 (NSF)	Field operations in Greenland	Available through 2017	
Survey aircraft	Arctic Domain Awareness Distribution and estimation of bird & mammal populations Shoreline mapping Habitat mapping Winter storm missions	**USCG**: C-130 aircraft based in Coast Guard Air Station Kodiak fly to the Chukchi and Beaufort seas to support Homeland Security missions, maritime domain awareness, and testing capabilities of personnel and equipment. As possible, scientists and sensors are accommodated. **NOAA:** NOAA contracts commercial aircraft for short range LIDAR/ remote sensing surveys. Longer range scientific aircraft (P3, GIV) also are contracted.	
Unmanned aerial vehicles	Physical, chemical, and biological measurements	**DOE:** Conduct flights and provide support for other users at Oliktok (Alaska) site by mid-2012. **NOAA:** Unmanned Aircraft System demonstrations ongoing for low altitude observing of spatial and temporal variability in marginal ice zone. Applications also being developed for vertical meteorological and atmospheric chemistry profiling, black carbon sampling, and wildlife surveys.	
Ocean-based			
Ice-capable research vessels	Physics, chemistry and biology of ice, ocean and atmosphere. Bathymetry.	**USCG:** The Coast Guard possesses three polar icebreakers (*Healy, Polar Star,* and *Polar Sea*). *Healy* remains active with an expected service life to 2030. *Polar Star* is undergoing an extensive overhaul intended to lengthen it	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.3, 3.4

		useable service life to approximately 2022 and is expected to be back in service in FY 2013. The *Polar Sea* will be decommissioned within the year. **UNOLS:** RV *Sikuliaq* available for research in early 2014. RV *Marcus G. Langseth* recently supported geophysical research in Arctic summer. **NOAA:** NOAA annually charters the R.V. *Khromov* from Russia to carry out the Russian-American Long-term Census of the Arctic—servicing a Bering Strait mooring array and observing climate impacts on sea ice, ocean conditions, and ecosystems. NOAA seasonally deploys the *Oscar Dyson* (fishery survey class) and hydrographic survey vessels, *Rainier* and *Fairweather*. **International:** Canadian Coast Guard ice breakers CCGS *Louis St. Laurent* and *Wilfred Laurier* have provided support to U.S. researcher in the Arctic. Various other European vessels potentially available. International partners (Korea, China, Japan, Russia, Canada) also sample in the Distributed Biological Observatory.	

Table 1. (continued)

INFRASTRUCTURE	USE	AVAILABILITY	SECTION
Ice camps/stations	Physics, chemistry and biology of ice, ocean and atmosphere. Bathymetry.	Ephemeral facilities that are occupied typically for periods of weeks to months, and less commonly for 1-2 years.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.3, 3.4
Sea ice-based autonomous observatories, e.g., ice-tethered profilers, flux buoys, ice mass balance buoys, wave buoys	Physics, chemistry and biology of ice, ocean and atmosphere.	Available, but development of new and improved sensors continues.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.3, 3.4, 3.5
Open ocean autonomous platforms, e.g., buoys, wavegliders, wave buoys	Physics, chemistry and biology of ice, ocean and atmosphere.	Available, but development of new and improved sensors and platforms continues.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.3, 3.4, 3.5
Unmanned underwater vehicles (UUV)	Physics, chemistry and biology of water; sea ice draft; bathymetry.	Short duration: available Long duration: not available, but under development.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.4, 3.5
Acoustic communication and navigation	Command and control, and data relay to shore, for UUVs and similar platforms	Not available.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.4
Submarines	Physics, chemistry and biology of water; sea ice draft; bathymetry.	US Navy Science Accommodation Missions (SAMs). Also occasional Royal Navy (UK) submarine missions.	3.1.1, 3.1.3, 3.1.4, 3.4, 3.5
Moorings	Physics, chemistry and biology of water; sea ice draft.	Available, but development of new and improved sensors continues.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.4, 3.5
Cabled ocean observatories	Physics, chemistry and biology of near-shore waters and ice, and real-time transmission of data; acoustic	Not available.	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.4, 3.5

	communication and navigation nodes.		
Land-based			
Arctic field stations	Measurement of physical, chemical, and biological parameters	CDC Arctic Investigations Program. Available for collaborative studies on human health and infectious diseases. DOE: Maintains a research site at Barrow, Alaska. A new site at Oliktok, Alaska will be operational mid-2013. The Next Generation Ecosystem Experiment is expected to operate on the Seward Peninsula and in Barrow, Alaska beginning in 2012. NSF: The NSF maintains research stations at Toolik Lake, Alaska and Summit, Greenland. In cooperation with NOAA and the Russian Federal Service for Hydrometeorology and Environmental Monitoring, NSF maintains an observatory site at Tiksi, Russia.	3.7
Data and information management			
Data exfiltration	Timely transfer of data from instruments in the field to people for data processing.	Time varies according to circumstances. There is increasing use of satellite communications, e.g., Iridium, for transfer from remote surface instruments. Not available for instruments below the surface leading to delays in data recovery and subsequent broader availability. Broadband communications remain a challenge in the Arctic.	Applies to all sections.
Data processing	QA/QC, preparation of data documentation,	Accomplished with varying degrees of quality and success. There is growing recognition	Applies to all sections.

	metadata profiles and data files, and placement in archives.	that research data must be properly processed and archived. NSF data policy provides guidance, requirements, standards.	
Data archiving	Long-term data curation and distribution services.	Available for many data sets, e.g., NASA EOSDIS, NOAA National Data Centers (NGDC, NODC, and NCDC), DOI/USGS EROS Center, DOE ARM and NGEE data archives. NSF Division of Arctic Sciences is funding the development of Advanced Cooperative Arctic Data and Information System for research data and Exchange for Local Observations and Knowledge in the Arctic for traditional knowledge. Inter-operability remains a challenge. Human subjects data and traditional knowledge require special handling due to privacy and data ownership concerns.	Applies to all sections.
Data standards	Adherence to standards from the moment data are acquired makes possible inter-operability of archives, data discovery, analysis and integration, and derived product development.	Data standards are in widespread use but are not necessarily uniform. Adoption of data standards by the scientific community as it accepts its role in responsible data and information management continuing to develop.	Applies to all sections.
Data agreements and access	Facilitate free and open data sharing and exchange nationally and internationally.	In the U.S., data are generally freely and openly available, but delays can occur between acquisition and availability in archives. Internationally, the situation is more variable; some countries charge fees and some do not release data.	Applies to all sections.
Communication and			

learning			
Web/internet connectivity	Outreach to indigenous and other communities; enhancing science literacy	DOE: The Atmospheric Radiation Measurement Climate Research Facility has ongoing outreach activities that provide educational materials and data access.	
Navigation (e.g., GPS) and communication tools (e.g., radios)	Enhance indigenous observations		
Models & Modeling			
Sea ice	CICE is a leading dynamic sea ice model. The Elastic-Viscous-Plastic dynamics within CICE is the dynamical basis for many other sea ice models.	NOAA: National Ice Center. ESRL/PMEL sea ice studies.	3.1, 3.5
Model intercomparison	Arctic Ocean Model Intercomparison Project		3.5
Regional Arctic models	Regional Arctic System Model		3.1, 3.2, 3.5