ARCTIC RESEARCH PLAN
FY2017-2021

PRODUCT OF THE
Interagency Arctic Research Policy Committee
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

December 2016

EXECUTIVE OFFICE OF THE PRESIDENT

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

WASHINGTON, D.C. 20502

December 9, 2016

Members of Congress:

I am pleased to forward the second five-year Arctic Research Plan produced by the Interagency Arctic Research Policy Committee (IARPC). Covering the period 2017-2021, the plan is one of IARPC's responsibilities described in the Arctic Research Policy Act of 1984 (15 U.S.C. § 4108).

The Arctic environment is undergoing rapid transitions as air temperatures increase, sea ice and land ice diminish, terrestrial snow cover declines, and permafrost warms and thaws. These physical changes have tremendous implications for marine and terrestrial ecosystems, human health and well-being, national security, transportation, and economic development in the Arctic and beyond. The United States, the other Arctic nations, and those non-Arctic nations with substantial Arctic research activities need strong, coordinated research efforts to understand and forecast changes in the Arctic.

Responding to this need, ten Federal agencies, departments, and offices collaborated to develop this plan, which calls for strong interagency communication, coordination, and collaboration within the framework of the National Science and Technology Council. The IARPC staff also consulted with collaborators in the State of Alaska, local communities, indigenous organizations, non-governmental organizations, and the academic community to ensure that the interests and needs of all stakeholders are addressed appropriately in this research plan.

Toward that end, and in furtherance of goals developed by the U.S. Arctic Research Commission, this plan focuses on those research activities that would be substantially enhanced by multi-agency collaboration. Many important investigations outside the scope of this plan will continue to be conducted within individual agencies or through other interagency collaborations.

I appreciate your support as this Administration works to ensure that the Nation's research efforts in the Arctic are broadly coordinated across the full spectrum of Federal agencies and interests.

Sincerely,

John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

NATIONAL SCIENCE FOUNDATION
4201 WILSON BOULEVARD
ARLINGTON, VIRGINIA 22230

OFFICE OF THE DIRECTOR

December, 2016

MEMBERS OF CONGRESS:

As required by 15 U.S.C. §4108, I am pleased to transmit this 2017-2021 plan of the U.S. Interagency Arctic Research Policy Committee (IARPC) that enhances and strengthens the U. S. federal Arctic research enterprise. Development of this 5-year plan entailed consultations with 14 federal agencies, the State of Alaska, local and indigenous organizations, the academic community and the broader public. The plan is broad in scope, but even so, does not represent the full breath of the US Government research on the Arctic. Each agency will continue to support additional research activities to meet its respective mission.

The changing Arctic presents challenges and opportunities for society both in the Arctic and globally. A diminishing sea ice cover is transforming ecosystems and altering subsistence activities as well as circumstances for commercial shipping, resource extraction and tourism. Glacial melt is contributing to sea level rise that can impact extensive coastal infrastructure and populations around the world. Thawing permafrost is impacting northern infrastructure and has potentially significant implications for the global carbon cycle. Changes in Arctic snow and ice covers may be linked to changing weather patterns in the lower latitudes of the northern hemisphere. The ability to understand and predict the future course of such changes is vital to the economy and security of the U.S. as an Arctic nation.

This plan builds on the experience with the successful format of the 2013-2017 IARPC 5-year plan. The focus is on priority Arctic research areas best addressed though interagency partnerships to ensure effectiveness and efficiency. The approach to the plan is purposefully dynamic in order to keep pace with observed changes. In particular, performance elements of the plan are intended to cover the next two years. Towards the end of that period, IARPC will make adjustments to respond to new knowledge and emergent needs.

Concurrently, IARPC will also continue to develop themes and ideas that arose during development of this plan. For example, IARPC wishes to engage northern communities more fully in all stages of research endeavors to identify and co-produce much needed knowledge to inform real-world issues such as coastal resilience and socio-economic trajectories. IARPC will also explore strengthening the linkage between Arctic research and Science, Technology, Engineering and Mathematics education in order to excite and motivate students and the future STEM workforce both in Arctic communities and throughout our nation.

I wish to acknowledge the contributions of all involved in producing this plan and, as Chair of IARPC, look forward to leading its successful and productive implementation in the years ahead.

Sincerely,

France A. Córdova
Director

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development (R&D) enterprise. One of the NSTC's primary objectives is establishing clear national goals for Federal science and technology investments. The NSTC prepares R&D packages aimed at accomplishing multiple national goals. The NSTC's work is organized under five committees: Environment, Natural Resources, and Sustainability; Homeland and National Security; Science, Technology, Engineering, and Mathematics (STEM) Education; Science; and Technology. Each of these committees oversees subcommittees and working groups that are focused on different aspects of science and technology. More information is available at www.WhiteHouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on questions in which science and technology are important elements; articulating the President's science and technology policy and programs; and fostering strong partnerships among Federal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC. More information is available at www.WhiteHouse.gov/ostp.

About the Interagency Arctic Research Policy Committee

The Arctic Research and Policy Act of 1984 (ARPA) Public Law 98-373, July 31, 1984, as amended by Public Law 101-609, November 16, 1990, provides for a comprehensive national policy dealing with national research needs and objectives in the Arctic. The ARPA establishes a U.S. Arctic Research Commission (USARC) and an Interagency Arctic Research Policy Committee (IARPC) to help implement the Act. IARPC was formally created by Executive Order 12501. Its activities have been coordinated by the National Science Foundation (NSF), with the Director of the NSF as chair. On July 22, 2010, President Obama issued a memorandum for the Director of the OSTP making NSTC responsible for the IARPC with the director of the NSF remaining as the chair of the committee.

About this Document

This report was developed by the IARPC which reports to the NSTC Committee on the Environment, Natural Resources and Sustainability (CENRS). This report is published by OSTP.

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Report prepared by

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Executive Summary

The United States is an Arctic nation—Americans depend on the Arctic for biodiversity and climate regulation and for natural resources. America's Arctic—Alaska—is at the forefront of rapid climate, environmental, and socio-economic changes that are testing the resilience and sustainability of communities and ecosystems. Research to increase fundamental understanding of these changes is needed to inform sound, science-based decision- and policy-making and to develop appropriate solutions for Alaska and the Arctic region as a whole.

Created by an Act of Congress[1] in 1984, and since 2010 a subcommittee of the National Science and Technology Council (NSTC) in the Executive Office of the President, the Interagency Arctic Research Policy Committee (IARPC) plays a critical role in advancing scientific knowledge and understanding of the changing Arctic and its impacts far beyond the boundaries of the Arctic. Comprising 14 Federal agencies, offices, and departments, IARPC is responsible for the implementation of a 5-year Arctic Research Plan in consultation with the U.S. Arctic Research Commission, the Governor of the State of Alaska, residents of the Arctic, the private sector, and public interest groups.

This 5-year plan—*Arctic Research Plan FY2017-2021*—has nine goals:

(1) Enhance understanding of **health determinants** and improve the **well-being** of Arctic residents;

(2) Advance process and system understanding of the changing Arctic **atmospheric composition and dynamics** and the resulting changes to surface energy budgets;

(3) Enhance understanding and improve predictions of the changing Arctic **sea ice cover;**

(4) Increase understanding of the structure and function of Arctic **marine ecosystems** and their role in the climate system and advance predictive capabilities;

(5) Understand and project the mass balance of **glaciers, ice caps, and the Greenland Ice Sheet,** and their consequences for sea level rise;

(6) Advance understanding of processes controlling **permafrost** dynamics and the impacts on ecosystems, infrastructure, and climate feedbacks;

(7) Advance an integrated, landscape-scale understanding of Arctic **terrestrial and freshwater ecosystems** and the potential for future change;

(8) Strengthen **coastal community resilience** and advance stewardship of coastal natural and cultural resources by engaging in research related to the interconnections of people, natural and built environments; and

(9) Enhance frameworks for **environmental intelligence** gathering, interpretation, and application toward decision support.

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[1]The Arctic Research and Policy Act of 1984 (ARPA), Public Law 98-373, July 31, 1984, as amended by Public Law 101-609, November 16, 1990, provides for a comprehensive national policy dealing with national research needs and objectives in the Arctic. The ARPA establishes an Arctic Research Commission and an Interagency Arctic Research Policy Committee (IARPC) to help implement the Act.

Each Goal is associated with **Research Objectives**—specific actions intended to benefit from coordinated, multi-agency, and possibly international research efforts, which are themselves associated with **Performance Elements**—tasks with concrete, measurable outcomes that demonstrate progress made toward satisfying the Research Objectives.

The Plan's nine Goals have a total of 34 Research Objectives and 123 Performance Elements. As with its predecessor—*Arctic Research Plan FY2013-2017*—this plan does not attempt to cover all Arctic research supported by the Federal Government. Rather, it addresses key topics for which an interagency approach is most likely to accelerate progress.

Consistent with U.S. Arctic Region Policy[2] and the *National Strategy for the Arctic Region*,[3] the Goals support U.S. policy across a range of scales, from Arctic people and communities to the global scale. The **policy drivers** for the Plan are:

(1) Enhance the **well-being** of Arctic residents;

(2) Advance **stewardship** of the Arctic environment;

(3) Strengthen national and regional **security**; and

(4) Improve understanding of the Arctic as a **component of planet Earth**.

The research conducted to implement these goals and support these policy drivers will be guided by four strategies: (1) support for basic and applied disciplinary research and broader systems-level, research-based modelling and synthesis; (2) sustainment of measurements supporting long-term observations and understanding of the Arctic System and mechanisms to provide timely and efficient access to data; (3) inclusion of Indigenous Knowledge holders and northern residents versed in Local Knowledge as generators of and collaborators in research; and (4) international collaboration that strengthens research, provides opportunities for improved research access to the Arctic, and makes the most effective use of costly infrastructure and logistics.

Implementation will take advantage of the collaborative infrastructure—IARPC Collaborations[4]—developed to implement *Arctic Research Plan FY2013-2017*. IARPC Collaborations is a platform for the research community to share information, generate ideas, and report on performance elements and thus advance toward achieving Research Objectives. Collaboration Teams responsible for each of the Goals include members from Federal agencies as well as outside partners such as the State of Alaska, Alaska Native organizations and communities, non-governmental organizations, academic institutions, and the private sector. IARPC Collaborations is open to any member of the research or stakeholder community who wishes to advance scientific knowledge of the Arctic.

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[2] National Security Presidential Directive/NSPD 66, Homeland Security Presidential Directive/HSPD 25: Arctic Region Policy, The White House, Washington DC, 2009

[3] National Strategy for the Arctic Region, The White House, Washington DC, 2013

[4] IARPC Collaborations: www.iarpccollaborations.org

Introduction

The Arctic and IARPC

The Arctic region touches the lives of all Americans.[5] Whether Alaska is home, an inspiring destination, or a vital source of economic prosperity and energy security, the only state in the Union with Arctic territory affects every U.S. citizen. Further, rapid environmental change is being observed throughout the Arctic, impacting the global system, with consequences for national interests and people around the world.

Created by Congress[6] and now a subcommittee of the National Science and Technology Council (NSTC) in the Executive Office of the President, the Interagency Arctic Research Policy Committee (IARPC) plays a critical role in advancing scientific knowledge and understanding of the changing Arctic through research planning. IARPC exercises this role through coordination across 14 Federal agencies[7] and collaboration with outside collaborators through its implementation structure—IARPC Collaborations.[8] Never has there been a better time and greater need for such strategic collaboration.

Since July 2010, when President Obama signed the Presidential Memorandum making the IARPC a subcommittee of the NSTC,[9] numerous dramatic environmental events have astonished Arctic observers. These include record-breaking warm air temperatures and end-of-summer minimum sea ice extent, extreme melting events on the Greenland ice sheet, and severe wildfire activity.

Changing long-term trends in the Arctic are also important. For example, annual minimum and maximum sea ice extents are decreasing at rates of 13.4 percent and 2.6 percent per decade, respectively, with many implications. One consequence of sea ice retreat is that Arctic coastal communities become more vulnerable to increasing ocean-surface wave heights, storm surges and inundation, and to coastal erosion accelerated by warming permafrost.

The consequences of sea ice retreat exemplify a system of interactions and feedbacks that amplify Arctic warming. These interactions and feedbacks indicate a need to **understand the individual components of the Arctic System**—the atmosphere, sea ice, marine, glacier, permafrost, terrestrial and freshwater ecosystems—at the same time as they urge an **understanding of how the system operates as a whole**,

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[5] About 30 percent of Alaska lies within the Arctic Circle, making the United States one of eight Arctic nations. To increase public understanding of this fact—and to draw connections between Alaska, the wider Arctic, and the rest of the country—the U.S. Department of State blog, “Our Arctic Nation,” is devoted to describing the connections between the Arctic and each of the 50 states in the Nation during the U.S. chairmanship of the Arctic Council (spring 2015-2017). www.medium.com/our-arctic-nation/welcome-to-our-arctic-nation-2d33796c63e8#.5dxqtfymd

[6] Arctic Research and Policy Act of 1984 (ARPA), Public Law 98-373, July 31, 1984, as amended by Public Law 101-609, November 16, 1990

[7] See Appendix 1.

[8] Through IARPC Collaborations, scientists share their work and team up to solve difficult problems. www.iarpccollaborations.org

[9] “Executive Order: Enhancing Coordination of National Efforts in the Arctic.” The White House, Office of the Press Secretary, January 21, 2015 www.WhiteHouse.gov/the-press-office/2015/01/21/executive-order-enhancing-coordination-national-efforts-arctic

in the context of the global system, to advance holistic understanding and support science-based policy decisions.

A complete understanding of the Arctic System must include the human component. Incorporating the complex human role in emerging Arctic research questions was a key recommendation of the National Academy of Sciences' report, *The Arctic in the Anthropocene: Emerging Research Questions,*[10] which, at the request of IARPC, looked 10 to 20 years into the future of Arctic research to make inquiry more targeted and effective. The role of people is also reflected in the growing need for social science in Arctic research, as recommended by the U.S. Arctic Research Commission (USARC) in its Report on the Goals and Objectives for Arctic Research 2015-2016.[11]

These recommendations are reflected in the complexity of the efforts described in this document, particularly where issues are tightly linked at the nexus of natural and human systems. For example, improved understanding of atmospheric processes and their impact on surface heating is linked to an improved understanding of cryospheric change. These, in turn, are linked to questions about the well-being of Arctic communities. For example, how will thawing permafrost impact infrastructure supplying fresh drinking water, or sea ice retreat and sea level rise affect the viability of coastal communities? Community responses to these stressors may in turn impact the future state of other components of the system, such as ecosystems or economies. Similar examples underscore the complex and linked relationship between the Arctic system and the global system.

The linked nature of these research domains inherently requires an Arctic System approach to research planning: one that views questions holistically in the context of interacting, interrelated, or interdependent components forming a complex whole. Support for decision-making in this context of the Arctic System requires frameworks for generating integrated environmental knowledge—Environmental Intelligence—that is timely, reliable, and suitable for the decisions at hand.

IARPC Arctic Research Plan 2017-2021

Policy Drivers

This document, *Arctic Research Plan 2017-2021* (hereafter "the Plan"), identifies critical areas where the U.S. Arctic research enterprise supports U.S. policy from community to global scales. The four policy drivers for the Plan are:

(1) Enhance the well-being of Arctic residents (*Well-being*). Knowledge will inform local, state, and national policies to address a range of goals including health, economic development, and the cultural vibrancy of Indigenous peoples and other Arctic residents;

(2) Advance stewardship of the Arctic environment (*Stewardship*). Results will provide the necessary knowledge to understand the functioning of the terrestrial and marine environments, and anticipate globally-driven changes as well as evaluate the potential impact of local actions;

(3) Strengthen national and regional security (*Security*). Efforts will include work to improve shorter-term environmental prediction capability and longer-term projections of the future state of the Arctic region to ensure security and emergency response agencies have skillful forecasts of

[10] Available for download on the IARPC Collaborations website: www.iarpccollaborations.org/about

[11] "Report on the Goals and Objectives for Arctic Research 2015-2016" www.arctic.gov/reports_goals.html

operational environments and the tools necessary to operate safely and effectively in the Arctic over the long term;

(4) Improve understanding of the Arctic as a component of planet Earth (*Arctic-Global Systems*). IARPC research will inform the important role of the Arctic in the global system, such as the ways the changing cryosphere impacts sea level, the global carbon and radiation budgets, and weather systems.

These policy drivers support the Nation's *Arctic Region Policy*[12] and its implementation through the *National Strategy for the Arctic Region* (NSAR).[13]

Research Goals

The Plan describes nine Research Goals, broad topics identified by IARPC as points where the interagency approach can accelerate progress. Six Goals represent components of the Arctic System and build upon the work of the previous IARPC Plan.[14] Two holistic Goals integrate understanding of components of the Arctic System to address the increasing complexity of research for understanding health determinants, and strengthening coastal resilience. The final Goal, environmental intelligence, supports the other eight and advances tools and approaches for informed decision-making.

The Research Goals are:

(1) Enhance understanding of **health determinants** and improve the **well-being** of Arctic residents;

(2) Advance process and system understanding of the changing Arctic **atmospheric composition and dynamics** and the resulting changes to surface energy budgets;

(3) Enhance understanding and improve predictions of the changing Arctic **sea ice cover;**

(4) Increase understanding of the structure and function of Arctic **marine ecosystems** and their role in the climate system and advance predictive capabilities;

(5) Understand and project the mass balance of **glaciers, ice caps, and the Greenland Ice Sheet,** and their consequences for sea level rise;

(6) Advance understanding of processes controlling **permafrost** dynamics and the impacts on ecosystems, infrastructure, and climate feedbacks;

(7) Advance an integrated, landscape-scale understanding of Arctic **terrestrial and freshwater ecosystems** and the potential for future change;

(8) Strengthen **coastal community resilience** and advance stewardship of coastal natural and cultural resources by engaging in research related to the interconnections of people, natural and built environments; and

[12] National Security Presidential Directive-66/Homeland Security Presidential Directive-25, January 2009

[13] *National Strategy for the Arctic Region*. Office of the President of the United States, May 2013 www.WhiteHouse.gov/sites/default/files/docs/nat_arctic_strategy.pdf

[14] *Arctic Research Plan: FY2013–2017* www.iarpccollaborations.org/plan/index.html

(9) Enhance frameworks for **environmental intelligence** gathering, interpretation, and application toward decision support.

Each Research Goal is supported by **Research Objectives**—specific actions that benefit from coordinated, multi-agency research efforts conducted in collaboration with local, regional, academic, and international collaborators; and **Performance Elements**—tasks with concrete, measurable outcomes that demonstrate progress toward satisfying the Research Objectives. Performance Elements each list a **Lead Agency**—the IARPC member agency responsible for coordinating the implementation of the task and reporting on progress—and **Supporting Agencies**—which assist the Lead Agency and whose research contributes to the implementation and reporting.[15] In many cases, agencies listed against Performance Elements are funding relevant work that is being conducted by academia or outside partners. Some Performance Elements have only one agency (e.g., 3.1.3 is a NASA-only project), but they generate data that are broadly catalytic or they represent valuable seed efforts with the potential for growing interagency engagement.

Implementation

This Plan builds upon its predecessor, *Arctic Research Plan FY13-17*, whose successes are highlighted in the IARPC biennial report.[16] In addition, for this Plan IARPC developed high-level strategies to guide implementation. They are to: (1) support a portfolio of basic and applied disciplinary research, and broader systems-level, research-based modelling and synthesis; (2) sustain measurements supporting long-term observations and understanding of the Arctic System, and mechanisms to provide timely and efficient access to data; (3) include Indigenous Knowledge[17] holders and northern residents versed in Local Knowledge[18] as generators of and collaborators in research; and (4) strengthen international collaboration in research, provide opportunities for improved research access to the Arctic, and make the most effective use of costly infrastructure and logistics.

This Plan's successful implementation will depend on the collaborative infrastructure, IARPC Collaborations,[19] which was created to carry out the previous plan and which was a noted accomplishment of the period. Collaboration teams include representatives from relevant Federal agencies that comprise IARPC, as well as outside collaborators from state and local governments,

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[15] Agencies are listed following standard usage guidelines: Federal departments appear first, followed by agencies in alphabetical order. Thus, the order of partner departments and agencies should not be construed to indicate priority.

[16] "Interagency Arctic Research Policy Committee 2015 Biennial Report." Committee on Environment, Natural Resources, and Sustainability, National Science and Technology Council, Office of Science and Technology, Office of the President www.WhiteHouse.gov/administration/eop/ostp/nstc/committees/cenrs/iarpc

[17] Indigenous Knowledge (IK) is here defined as a systematic way of thinking applied to phenomena across biological, physical, cultural, and spiritual systems. It includes insights based on evidence acquired through direct and long-term experiences and extensive and multigenerational observations, lessons, and skills. IK has developed over millennia and continues in a living process, including knowledge acquired today and in the future, and it is passed on from generation to generation (ICC-Alaska. 2015).

[18] Local Knowledge (LK) is here defined as knowledge tied to a place and acquired via experience and observation. Unlike IK, it does not require a multi-generational accumulation of knowledge.

[19] See Appendix 2.

academic institutions, non-government organizations (NGOs), and community members. People from these diverse backgrounds all work together to enact the Performance Elements.

Implementation of Performance Elements in this Plan is focused on the period 2017-2018, with some exceptions for projects and programs to which agencies have made commitments that extend beyond 2018. As new opportunities or needs for observations, understanding, and responses arise, IARPC will add Performance Elements.

As with its predecessor, this Plan does not attempt to address all Arctic research supported by the Federal Government or recommended by the U.S. Arctic Research Commission.[20] Many important single-agency efforts are not included because of this plan's emphasis on interagency collaboration. Additionally, other interagency bodies such as the National Ocean Council (NOC), the NSTC Subcommittee on Ocean Science and Technology (SOST), and the U.S. Global Change Research Program (USGCRP) cover other critical Arctic research topics and interagency coordination, e.g., ocean acidification. The Arctic Executive Steering Committee (AESC) is responsible for coordinating all Federal Government activities in the Arctic, and for the implementation of the NSAR. Some efforts with potentially relevant research components, such as renewable energy, are currently being organized under AESC; as specific research needs are identified, their coordination may be adopted by IARPC. Efforts arising from this Plan contribute to the implementation of the NSAR, particularly the *Responsible Arctic Region Stewardship* line of effort.

The urgency of Arctic change and complexity of Arctic research compel innovative means for advancing understanding. In the last five years, IARPC has built a successful network of collaborators through a creative implementation strategy, which complements interagency coordination with outside collaboration. This Plan aims to capitalize upon the strength of that growing network to advance knowledge and decision support for the challenges and opportunities that lie ahead.

[20] See Appendix 3.

Research Goal 1: Enhance Understanding of Health Determinants and Improve the Well-being of Arctic Residents

Arctic societies are known for their historic capacity for adaptation and resilience. But, northern residents are now facing an unprecedented combination of climate and environmental change, new opportunities for commercial and industrial development, and social and economic transformations (Arctic Human Development Report 2004; Arctic Human Development Report II 2014). Such changes present significant challenges and opportunities. For example, the rapidly changing environment in the Arctic poses new risks to food, water, and energy security with implications for the health and well-being of Arctic residents. This is an opportunity for Federal agencies to work collaboratively with Arctic residents on research to foster adaptation and mitigation strategies to meet emerging needs.

State, local, and tribal authorities—and community members themselves—may be confronted with critical choices based on anticipated threats: stronger and more frequent storms, increasing coastal erosion, thawing permafrost, changing marine mammal and bird migration patterns, ocean acidification, sea level rise, changes in local vegetation due to warmer temperatures, and increased fires. Further, many Arctic populations are also experiencing heritage and language loss, shifting economies, population migration, mental illness, and high rates of suicide. Arctic residents need reliable and timely data and innovative research approaches to make knowledge-based decisions that consider the immediate and future impacts on existing infrastructure and community services, human health, subsistence activities, cultural and linguistic vitality, and overall food security.

A coordinated, evidence-based, government-wide plan can help support and strengthen the capacity of Arctic residents to adapt and respond to new challenges. Consistent with recommendations from the Alaska Arctic Policy Commission (AAPC 2015) and Indigenous organizations such as the Inuit Circumpolar Council (ICC Arctic Policy 2016), efforts are being made to use Indigenous Knowledge (IK) and/or Local Knowledge (LK) in community-based research and to use multiple knowledge systems to inform management, health, and environmental decisions.

The following Research Objectives reflect this integrated approach to Federal research commitments directly related to the *Well-being* policy driver, with implications for *Stewardship* and *Security* drivers as well. The determinants of health and well-being are wide-ranging, and it is beyond the scope of this Plan to catalog all of the research, programs, or services related to the health of Arctic residents. Instead, the Health and Well-being Goal is focused mainly on Federally-funded research activities that feature interagency collaborations and that are expected to produce tangible results during the time-span of this Plan. There are many excellent examples of ongoing health research that do not fit these criteria and are not included herein.

Research Objective 1.1. Support integrative approaches to human health that recognize the connections among people, wildlife, the environment, and climate.

Rationale*:* The circumpolar North is vulnerable to the health impacts of climate change. A "One Health" approach to these vulnerabilities recognizes that human health, animal health, and ecosystem health are inextricably linked. This is particularly true in subsistence communities, where a One Health approach can link networks of diverse knowledge holders and transdisciplinary specialists to advance understanding of complex climate-associated health risks and to provide community-based strategies for early identification and mitigation of health risks in humans, animals, and the environment (Ruscio et al. 2015).

Performance Element 1.1.1: In collaboration with the Alaska Native Tribal Health Consortium (ANTHC), advance and support a regional One Health approach for assessing interactions at the Arctic human-animal-environment interface to enhance understanding of, and response to, the complexities of climate change for Arctic residents.

Lead Agencies: DOI (FWS), HHS (CDC), EPA, NOAA, USDA (NIFA)
Supporting Agencies: DOI (USGS), DOS, NASA

Performance Element 1.1.2: In collaboration with the ANTHC, support community-based monitoring and IK and LK by maintaining and strengthening the Local Environmental Observer (LEO) Network to help describe connections between climate change, environmental impacts, and health effects.

Lead Agencies: DOI (BOEM, FWS), EPA
Supporting Agencies: NOAA, NSF

Performance Element 1.1.3: In coordination with the ANTHC, use the Alaska Native Maternal Organics Monitoring Study (MOM) to monitor the spatial distribution, contaminant levels, and biological effects in species having body burdens of human caused Persistent Organic Pollutants[21] (POPs) at or above levels of concern; and improve understanding of the adverse effects of POPs on human populations, especially on child development.

Lead Agencies: HHS (CDC), EPA
Supporting Agency: NOAA

Performance Element 1.1.4: Increase understanding of how both natural climate change and the effects of human activities are affecting the ecosystem by documenting observations of changing sea ice conditions, with implications for development and subsistence. Efforts like Arctic Crashes: Humans, Animals in a Rapidly-Changing World and Northern Alaska Sea Ice Project Jukebox are examples of contributions to this performance element.

Lead Agencies: DOI (BOEM), NOAA, USDA (NIFA), NSF, SI
Supporting Agency: DOI (NPS)

Performance Element 1.1.5: Together with the ANTHC, State of Alaska Department of Fish and Game, and the University of Alaska Fairbanks (UAF), support the Rural Alaska Monitoring Program (RAMP), a community-based environmental monitoring network in Alaska Native communities to collect samples and data on zoonotic pathogens, mercury, and organic contaminants in land and sea mammals used for subsistence. Test marine bivalves for contaminants, mercury, and the toxins responsible for paralytic and amnestic shellfish poisoning; test mosquitos for the agent of tularemia; and test community water for cyanobacterial toxins.

Lead Agencies: DOI (FWS), HHS (CDC), NOAA, EPA

Research Objective 1.2. Promote research, sustainable development, and community resilience to address health disparities associated with underlying social determinants of health and well-being.

[21] POPs are hazardous organic chemical compounds that are resistant to biodegradation and thus remain in the environment for a long time, adversely affecting human health.

Rationale: Health is influenced by a wide range of social, economic, and ecological factors; indeed, there is a clear link between the social determinants of health and health inequalities (Reading and Wien 2009). Hence, it is important to understand social-ecological systems and how they influence the health and well-being of individuals and communities.

Performance Element 1.2.1: In collaboration with the ANTHC and the State of Alaska, support development of Arctic Water, Sanitation and Hygiene (WASH) innovations and characterize the health consequences associated with decreased access to in-home water and sanitation services.

Lead Agencies: HHS (CDC, IHS), USDA, EPA, USARC
Supporting Agency: DOS

Performance Element 1.2.2: Together with the ANTHC, the Commission for Environmental Cooperation, the Yukon Kuskokwim Health Corporation, and Bristol Bay Health Corporation, support research on the health impacts of poor indoor air quality, especially in children. Support source testing and technologies to improve indoor air quality.

Lead Agencies: HHS (CDC, IHS), HUD, EPA

Performance Element 1.2.3: Support educating and connecting Arctic residents with museum collections and archival materials to improve community mental health and well-being through efforts such as The Health of Heritage.

Lead Agencies: Department of Education, NOAA, LC, SI
Supporting Agencies: DOI (NPS), NSF

Performance Element 1.2.4: Through efforts like the Arctic-FROST[22] Research Coordination Network, synthesize knowledge on sustainable development among Arctic communities; develop a state-of-the-art understanding of social-ecological systems in the Arctic context; and amass case studies of best practices that support well-being and sustainable development across the Arctic. Deliverables will include coordinated educational activities, presentations, and validation of research results through researcher/community workshops and educational initiatives that involve youth, Indigenous scholars, early career scientists, and members of underrepresented groups.

Lead Agency: NSF

Research Objective 1.3. Promote food, water, and energy security in rural/remote Arctic regions.

Rationale: Significant disparities exist between Arctic and non-Arctic residents related to the availability and affordability of traditional and non-traditional foods; the quality and quantity of water available (and its related health benefits); and the cost and options for energy production, conservation, and use (especially for residential home heating).

Performance Element 1.3.1: In collaboration with the State of Alaska, coordinate investigations and reporting on food security in the Arctic, to include shifting patterns of food consumption, the safety of subsistence foods, and successful adaptation strategies being employed by northern residents.

[22] Arctic Frontiers Of Sustainability: Resources, Societies, Environments and Development in the Changing North

Lead Agencies: DOI (BOEM)
Supporting Agencies: NOAA, NSF

Performance Element 1.3.2: In collaboration with the Alaska Department of Environmental Conservation (ADEC) and the Alaska Rural Water and Sanitation Working Group, support the ADEC "Alaska Water and Sewer Challenge" and provide input and support for the Conference on Water Innovations for Healthy Arctic Homes (WIHAH) and its resultant research activities and recommendations.

Lead Agencies: HHS (CDC, IHS), USDA, EPA, USARC
Supporting Agency: DOS

Performance Element 1.3.3: Together with the Alaska Energy Authority (AEA), the Cold Climate Housing Research Center (CCHRC), and UAF, promote research on renewable, efficient, and sustainable (resource, maintenance, and cost) energy systems, including microgrid technology development and application in remote Arctic communities via USARC's Arctic Renewable Energy Working Group activities.

Lead Agency: USARC

Research Objective 1.4. Document the prevalence and nature of violence against Alaska Native women and youth; evaluate the effectiveness of Federal, State, Tribal, and local responses to violence against Alaska Native women and youth; and propose recommendations to improve the effectiveness of such responses.

Rationale: Victims of psychological aggression, physical violence, sexual violence, and stalking experience severe and negative health and social consequences, including poorer physical and mental health and lower employment status. Further, evidence suggests that Arctic Indigenous populations are disproportionately impacted (e.g., Pauktuutit Inuit Women of Canada 2006). Because there is a dearth of scientific research regarding victimization experiences of Alaska Native women, the USARC's Report on the Goals and Objectives for Arctic Research (2015-2016) identified domestic violence in the Arctic as an area of concern. Hence, accurate, comprehensive, and current information on the incidence, prevalence, and nature of intimate partner violence, sexual violence, and stalking in Alaska Native villages is needed to improve societal understanding of the programmatic, service, and policy needs of victims and to educate policy makers and the public about this pervasive threat to the health and well-being of Alaska Native women.

Performance Element 1.4.1: Together with the American Indian Development Associates (AIDA) and RTI International, conduct a National Baseline Study (NBS), also referred to as the Tribal Study of Public Safety and Public Health Issues Facing American Indian and Alaska Native Women, to assess Alaska Native women's experiences with violence and victimization, health and wellness, community crime, service needs, and help-seeking behaviors and outcomes. The NBS will produce a deeper understanding of public safety issues, quantify the magnitude of violence and victimization, provide accurate data to develop prevention and intervention strategies, and evaluate the response to violence by all levels of government.

Lead Agencies: DOJ (NIJ, OVW)

Performance Element 1.4.2: Together with the State of Alaska Department of Public Safety and the University of Alaska Anchorage, examine the contributions Village Public Safety Officers (VPSO) make to their rural communities and the criminal justice responses to violence committed against Alaska Native women. Evaluate and document the impact that the Alaska VPSO initiative is having on the investigation and prosecution of those who commit acts of sexual and domestic violence against Alaska Native women in rural communities, and determine the applicability of the VPSO model to other tribal communities in the United States.

Lead Agencies: DOJ (NIJ, OVW)
Supporting Agency: NSF

Performance Element 1.4.3: Together with the AIDA, determine effective methods to assess exposure to violence and victimization among Alaska Native youth, ultimately to improve their health and well-being. Develop and test a survey instrument and different administration modes that can effectively evaluate exposure to violence and victimization and determine the feasibility of using these procedures in tribal communities.

Lead Agencies: DOJ (NIJ, OJJDP, OVC)

Research Objective 1.5. Increase understanding of mental health, substance abuse, and well-being for Alaskan youth; and support programs that address those impacts and strengthen youth resilience.

Rationale: Increasing evidence suggests that childhood trauma can lead to serious health problems that last into adulthood and limit individuals from reaching their full potential. Research regarding mental health, substance abuse, and well-being in Arctic and sub-Arctic communities can strengthen youth resilience and support individual achievement, leading to improved health outcomes.

Performance Element 1.5.1: Increase knowledge and the evidence base for effective community-determined approaches that contribute to the health and well-being of children and youth as they move into adulthood. Efforts like Native Youth Initiative for Leadership, Empowerment, and Development (I-LEAD) and Generation Indigenous are examples of contributions to this performance element.

Lead Agencies: Department of Education, DOI (BIE), HHS (ACF), USDA (NIFA)

Performance Element 1.5.2: Support tribal behavioral health programs and collaborative research hubs to prevent and reduce suicidal behavior and substance abuse and to reduce the burden of suicide and promote resilience among Alaska Native youth. The research hubs are intended to increase the reach and research base for effective, culturally relevant, preventive interventions that will increase resilience and reduce suicide in Alaska Native communities.

Lead Agencies: HHS (CDC, NIH, NIMH, NIMHD), USARC
Supporting Agencies: DOS, NSF

Performance Element 1.5.3: Conduct surveys to document and report on adverse childhood experiences (ACEs) in Alaska children, including among American Indian and Alaska Native children.

Lead Agencies: HHS (CDC), DOC (Census Bureau), HHS (HRSA)

Research Objective 1.6. Support the reduction of occupational safety and health (OSH) hazards in the Arctic, particularly in the commercial fishing, water, and air transportation industries as well as for those workers exposed to occupational hazards from climate change impacts.

Rationale: Historically, Alaska has had a very high work-related fatality rate associated with its unique composition of industries and work settings. Recognizing that occupational safety and health hazards vary across industries and work settings in the Arctic, it is vital to establish a regional focus to advance understanding of OSH hazards and effective interventions needed for this unique state.

Performance Element 1.6.1: Together with the State of Alaska, document and describe occupational risks using epidemiologic surveillance.

Lead Agencies: DHS (USCG), DOL (OSHA), HHS (CDC), FAA, NTSB,

Performance Element 1.6.2: Together with the State of Alaska, conduct prevention-oriented research addressing fatal and nonfatal injuries and illnesses in high-risk worker populations.

Lead Agencies: DHS (USCG), DOL (OSHA), HHS (CDC), FAA, NTSB,

Research Objective 1.7. Improve the quality, efficiency, effectiveness, and value of health care delivery in the Arctic.

Rationale: Arctic health systems have a unique set of challenges to contend with and many health disparities in the access to, cost of, and quality of care exist between people in a given nation's Arctic regions and their larger, non-Arctic population. Hence, accurate and reliable data are critical to the development of more effective health care delivery approaches.

Performance Element 1.7.1: In collaboration with the ANTHC, promote research on how telemedicine applications can improve health care delivery and patient outcomes.

Lead Agency: HHS (AHRQ)

Research Goal 2: Advance Process and System Understanding of the Changing Arctic Atmospheric Composition and Dynamics and the Resulting Changes to Surface Energy Budgets

Over the industrial period, Arctic surface air temperature has increased more rapidly than in other parts of the globe due to a complex interplay of processes—a phenomenon called “Arctic Amplification” (Serreze and Barry 2011). Mechanisms and feedbacks governing atmosphere-surface heat exchange (i.e., meridional [north-south] heat transport and radiative forcing[23]), coupled with changing surface properties, drive this enhanced warming. Conversely, changes in Arctic conditions may impact circulation that changes weather and climate patterns over the Northern Hemisphere (Cohen et al. 2014) and beyond.

To address all IARPC policy drivers, IARPC collaboration teams must advance an integrated understanding of atmospheric processes as well as the resulting radiative forcing in the Arctic. The Arctic atmosphere is linked through large-scale circulation with global weather and climate systems (*Arctic-Global System*). Regionally, atmospheric processes drive changing weather patterns and influence sea ice amounts and distribution, knowledge of which is critical for managing emergency response and law enforcement efforts (*Security*). These changing weather patterns and sea ice distributions, along with changes in precipitation, snow cover, and permafrost melting, affect terrestrial ecosystems and other environmental conditions that alter subsistence systems and how Arctic residents interact with their environment. Further, changes in the environment have led to increased wildfire activity in the Arctic and at lower latitudes, causing air quality problems (*Well-being*) for Arctic residents (Kasischke et al. 2010).

The atmosphere links with many of the interdependent components of the Arctic climate system—the ocean and marine ecosystems, sea ice, land surface and permafrost, and terrestrial ecosystems. Accordingly, the Atmosphere Goal is linked to several other Goals that focus on these systems and with Environmental Intelligence. The interface between each of these climate sub-systems and the atmosphere can be measured by the surface energy budget (heat and radiation) and fluxes of moisture, aerosol, and gases (Bourassa et al. 2013). Characterizing these energy and mass fluxes across the Arctic is essential for understanding the future state of Arctic weather and climate. But a paucity of detailed observations of each of these atmospheric constituents over the different Arctic surface types precludes definitive, empirically-based understanding of the trends and variability in heat and mass fluxes over different domains and seasons and of the various radiative forcing mechanisms that control this variability.

Atmospheric constituents that drive radiative forcing—aerosols, clouds, and gases—affect the radiation and energy budget in the Arctic differently than at lower latitudes due to unique surface, atmospheric stability, and solar intensity states. Aerosols can change the Arctic radiation balance through direct radiative forcing of the atmosphere (Quinn et al. 2008), through aerosol-cloud indirect effects (e.g., de Boer et al. 2013), or by lowering the albedo of (typically) bright Arctic surfaces after deposition of black carbon or other absorbing species, potentially hastening snow and ice melt (Flanner et al. 2007). The abundance of aerosols and some gases (e.g., ozone) in the Arctic are affected by transport and removal processes between source regions at lower latitudes and the Arctic. Improving quantitative

[23] The change in radiative fluxes in the atmosphere resulting from a perturbation by atmospheric constituents such as clouds, aerosols, and gases.

understanding of these processes at lower latitudes and within the Arctic is key to improving predictability of Arctic climate forcing (AMAP 2015; Arnold et al. 2016).

Due to seasonally low sun angles and high surface albedos and the absence of solar radiation during the polar night, Arctic clouds have a limited ability to cool the surface by reflecting solar energy, but cloud infrared radiation significantly warms the surface (Intrieri et al. 2002). As a result, the net annual cloud radiative forcing at the Arctic surface is positive (a warming), opposite to the global cloud radiative effect. The Arctic cloud radiative forcing and its seasonal variability plays a critical role in modulating the surface energy budget and thereby affects the state of sea ice, ice sheets, permafrost, and snow cover (Kwok and Untersteiner 2011). Cloud forcing is dictated by lifetime, physical properties, and precipitation, which are governed by complex interactions between local- and large-scale processes involving dynamics, moisture supply, and aerosol influences on cloud nucleation (Garrett and Zhao 2006). The greatest challenge for those studying Arctic clouds currently is in understanding and representing the controls on cloud phase (Shupe 2011; Morrison et al. 2012).

In addition to cloud and aerosol influences on radiative forcing, Arctic carbon stores have the potential to greatly impact future climate states. The Arctic contains vast amounts of sequestered carbon in permafrost and marine hydrates, with an uncertain potential for CO_2, methane, and other releases into the atmosphere (AMAP 2015). Methane has a global warming potential (GWP) 28 times that of carbon dioxide (CO_2) per molecule, averaged over a 20-year period: though the atmospheric lifetime of methane is about a decade, that of CO_2 is several hundred years. When considering methane's 12-year atmospheric lifetime, its GWP increases to 84 times that of carbon dioxide over 20 years (IPCC, 2014). Understanding current methane emissions and potential scenarios under a warmer Arctic is imperative. Many global circulation models overlook carbon feedback loops from Arctic tundra; carbon release from thawing and decomposing tundra could, in turn, further accelerate carbon release—a scenario known as the Permafrost Carbon Feedback. Observations and recent analyses indicate that warming has not led to significant methane release from the permafrost (Sweeney et al. 2016); but the distribution of measurements precludes a definitive determination of methane sources and their strengths.

The Atmosphere Goal focuses on advancing observational systems of atmospheric constituents and surface energy fluxes, synthesizing existing and planned observations and models for better process understanding, and working within IARPC Collaborations to enhance knowledge of how the Arctic atmosphere and other parts of the climate system interface to produce the observed Arctic amplification and the corresponding observed changes in surface air temperature and sea ice loss. The team will draw from a range of surface-based observational systems maintained by multiple agencies including the long-term National Oceanic and Atmospheric Administration (NOAA) Barrow, Alaska Observatory, National Aeronautics and Space Administration's (NASA) Aerosol Robotic Network (AERONET) and Micro-Pulse Lidar (MPL) networks, and the Department of Energy's (DOE) facilities on the North Slope of Alaska, among others. Sub-orbital measurements from manned and unmanned aircraft will be exploited whenever possible, and support for enhancing and providing uniformity in both surface-based and sub-orbital observations will be pursued. The satellite contributions to this effort include top-of-atmosphere energy balance measurements from instruments such as Clouds and the Earth's Radiant Energy System (CERES), vertical distributions of aerosols and clouds from space-based lidar such as Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and aerosol amount and type mapping, mainly over smoke and pollution source regions in the sub-Arctic from Moderate-resolution Imaging SpectroRadiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR), Ozone Monitoring Instrument (OMI), and Visible Infrared Imaging Radiometer Suite (VIIRS), which, when combined with aerosol transport modeling, provide constraints on the flux of aerosols to the polar region.

Research Objective 2.1. Advance understanding of Arctic atmospheric processes and their integrated impact on the surface energy budget.

Rationale: The surface energy budget represents a critical coupling of the atmosphere to other sub-systems in the Arctic System (e.g., ocean, sea ice, and permafrost). Closing the surface energy budget over different surface cover types would represent a significant improvement in understanding atmospheric drivers of climate change in the Arctic, and the response of the integrated system to external forcers. Individual observing networks currently have inadequate coverage for closing the budget, but expanding measurement capabilities through external collaborations along with better coordination of available information sources can improve characterization, understanding, and modeling of this system.

Performance Element 2.1.1: Support planning, preparation, and implementation for the Multi-disciplinary drifting Observatory for the Study of the Arctic Climate (MOSAiC), including deployment of the DOE Atmospheric Radiation Measurement (ARM) mobile atmospheric measurement facility and other coupled measurements on the drifting German icebreaker, RV Polarstern, designed to fill observational gaps of radiation and heat fluxes and atmospheric constituents in the Arctic interior over open ocean and sea ice domains.

Lead Agencies: DOE, NSF
Supporting Agencies: NOAA, DOD (ONR)

Performance Element 2.1.2: Improve uniformity and accessibility of surface radiative and heat flux information from satellite retrievals and airborne and ground-based measurements to quantify spatial variability of the surface energy budget over land, ice, and open ocean environments in the Arctic. Augment efforts through IARPC Collaborations to integrate surface radiative and heat flux measurements with cryospheric process understanding and modeling efforts.

Lead Agency: NOAA
Supporting Agencies: DOE, NASA, NSF

Research Objective 2.2. Improve understanding of the composition of the Arctic atmosphere (moisture, clouds, precipitation, aerosols, and gases) and their net radiative effects and impact on Arctic climate.

Rationale: Changes in chemistry, moisture, and atmospheric state drive radiative forcing through a complex set of processes and interactions (Morrison, et al. 2012; de Boer et al. 2012). Long-term, continuous measurements at the surface are necessary to monitor trends in atmospheric composition, but must be complemented by in situ aerial measurements to provide process-level understanding and to fill observational gaps over regions and domains (e.g., sea ice and open ocean) that are not accessible from fixed site locations. Information describing the vertical structure of atmospheric constituents is critical to determining how and when the different constituents interact and their radiative effects. Measurements to gain such information are achievable through manned and unmanned aircraft programs, ground-based observations, and satellites.

Performance Element 2.2.1: Maintain and enhance support for fixed ground sites that contribute to long-term observations of Arctic atmospheric components using in situ and remote sensing measurements of atmospheric state parameters, gases, aerosols, and clouds (e.g., the DOE ARM sites at Barrow and Oliktok, the NOAA Global Monitoring Division Barrow Observatory, and NASA AERONET measurements). Improve uniformity in the suite of measurements and data products across sites to provide "network" information for increased physical understanding and representation of the Arctic climate system through International Arctic Systems for Observing the Atmosphere (IASOA) Working Groups and other integrative data and analysis efforts.

Lead Agencies: DOE, NOAA
Supporting Agencies: NASA, NSF

Performance Element 2.2.2: Continue support for and planning and analysis of past and potential future aircraft missions (e.g., NASA Atmospheric Tomography Mission—AToM—and air Pollution in the Arctic: Climate, Environment, and Societies—PACES[24]) that contribute observations of atmospheric composition and relevant processes such as transport, deposition, and radiation.

Lead Agency: NASA
Supporting Agencies: DOE, NOAA, NSF

Performance Element 2.2.3: Improve vertical and regional characterization of atmospheric gases, aerosol, and cloud properties through the use of existing, long-term data sets (e.g., the DOE ARM archive, the NOAA Network for the Detection of Atmospheric Composition Change—NDACC), together with new measurements, in underrepresented Arctic regions. Develop a better understanding of the representative nature of fixed sites by describing the range of conditions that exist across the Arctic through synthesis activities such as IASOA working groups.

Lead Agency: NOAA
Supporting Agencies: DOE, NASA, NSF

Performance Element 2.2.4: In collaboration with efforts described under the Permafrost Goal, support observation syntheses of atmospheric carbon to provide better process understanding of the relationships between warming and soil carbon release in the Arctic. Integrate atmospheric measurements with related observations and modeling of land surface and environmental parameters to advance this process understanding.

Lead Agencies: NOAA, NASA
Supporting Agencies: DOE, NSF

Research Objective 2.3. Improve understanding of the processes that control the formation, longevity, precipitation, and physical properties of Arctic clouds; the spatio-temporal distributions of aerosol types; and Arctic cloud and aerosol modulation of the surface radiation budget.

Rationale: Arctic clouds are governed by complex interactions between local- and large-scale processes that involve dynamics, moisture supply, and aerosol influences on nucleation. Aerosol populations follow a distinct seasonal pattern in the Arctic, but with spatio-temporal variability, that is not adequately characterized. Each of these variables is influenced by the location (e.g., along a particular transport pathway) and surface cover (e.g., open leads in sea ice) over which clouds form and where aerosols are

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[24] A joint initiative of the International Arctic Science Committee (IASC) and the International Global Atmospheric Chemistry (IGAC) project

produced or removed from the atmosphere. Of particular interest, due to the associated radiative forcing potential, is the opportunity to understand and represent the controls on cloud phase, which feed back onto cloud longevity, radiative properties, precipitation, and the horizontal and vertical distribution of different aerosol types across the Arctic.

Performance Element 2.3.1: Support and synthesize multi-platform observations of cloud and aerosol properties from surface, airborne, and space-borne instruments (integrated with models as appropriate) to describe the physical and radiative characteristics of cloud and aerosol over a range of spatio-temporal scales and over a range of Arctic land cover domains.

Lead Agency: DOE
Supporting Agencies: NOAA, NASA, NSF

Performance Element 2.3.2: Support integrated observational and modeling studies of atmospheric processes and their relationship to land cover that will increase understanding of the characteristics, evolution, and radiative properties of Arctic clouds and their interactions with aerosol, leading to advancement in representing clouds in models at many scales.

Lead Agency: DOE
Supporting Agencies: NOAA, NASA, NSF

Performance Element 2.3.3: In collaboration with efforts described under the Terrestrial Ecosystems Goal, understand the impacts of Arctic and Boreal Forest wildfires on emissions, distributions, weather, and climate impacts of biomass burning plumes through improved use of emissions databases and chemical transport modeling. Gain better understanding of deposition processes through studies and better characterization of the spatial (horizontal and vertical) distribution of biomass burning aerosol, especially in the Arctic interior over sea ice.

Lead Agency: NOAA
Supporting Agency: DOE

Performance Element 2.3.4: In collaboration with efforts described under the Environmental Intelligence Goal, support evaluation of reanalyses and their ability to represent Arctic clouds and controlling parameters with fidelity using satellite, aircraft, and ground-based observations.

Lead Agency: NASA
Supporting Agencies: NOAA, NSF

Research Goal 3: Enhance Understanding and Improve Predictions of the Changing Arctic Sea Ice Cover

Arctic sea ice is a geophysical phenomenon within a socio-ecological system, and as such it provides a variety of services (Eicken et al. 2009). They are: *regulating services*, e.g., the impact of sea ice on the surface energy budget plays a vital role in regulating the global climate; *provisioning services*, e.g., sea ice yields food for communities that harvest marine mammals for which the ice is a habitat; *cultural services*, i.e., non-material benefits of a cultural, spiritual, and educational nature contributing to the daily life of communities; and *supporting services*, e.g., micro-organisms, although not harvested directly, are an important component of a food web that sustains marine mammals and fish. Viewed from this geophysical/socio-ecological perspective, enhancing understanding and improving predictions of the changing sea ice cover will benefit from cooperation between sea ice researchers and numerous potential collaborators, including northern residents, who have particular Local and Indigenous Knowledge of the ice.

The Arctic sea ice cover is changing dramatically. The end-of-summer minimum sea ice extent (areal coverage) and the end-of-winter maximum sea ice extent have decreased by 40 percent and 9 percent, respectively, over the course of the satellite passive microwave observation period 1979-2015 (Fetterer et al. 2002, updated daily). The age and thickness distributions of the ice cover are also decreasing as the area of seasonal ice increases at the expense of the older, thicker perennial ice (Kwok and Rothrock 2009; Perovich et al. 2015). The resultant decrease in sea ice volume contributes to an increase in observed ice drift speeds (Kwok et al. 2013), and is likely responsible for higher deformation and ridging rates (Zhang et al. 2012). Pressure ridges are the thickest sea ice features and result from collisions between moving ice floes.

As the sea ice changes, there are many environmental and socio-ecological consequences. They include: direct effects on marine ecosystems and northern communities (Harwood et al. 2015; Kedra et al. 2015; Pearce et al. 2015; Ray et al. 2016; Tremblay et al. 2015), and indirect effects on terrestrial ecosystems (Bhatt et al. 2013); increasing ocean surface wave height, storm surge intensity, and coastal erosion and inundation (Overeem et al. 2015; Vermaire et al. 2014; Thomson and Rogers 2014) that threaten habitats, northern communities, and civil and defense infrastructure (Gibbs and Richmond 2015); rising sea surface temperatures (Timmermans and Proshutinsky 2015) and ocean primary production (Frey et al. 2015); a reduction in the earth's reflectivity, accounting for about 25 percent of the warming due to increasing atmospheric CO_2 (Pistone et al., 2014); and tropospheric warming, which is amplifying global warming in the Arctic (Serreze and Barry 2011), and might be weakening the jet stream and contributing to more extreme weather in mid-latitude regions (e.g., Francis et al. 2014).

The changing sea ice cover, particularly the decreasing minimum extent and associated increase in the area of summer open water, is opening the region to increased ship traffic for cargo and tourism (e.g., Stephenson and Smith, 2015) and extraction of natural resources such as oil and gas, minerals, and fish (e.g., National Petroleum Council, 2015). In turn, growth in such activities has implications for homeland and national security such as search and rescue policy, oil spill preparedness and response, and domain awareness. Current model projections of sea ice extent show that a nearly ice-free Arctic Ocean at the end of summer is a distinct possibility later this century, although there remains considerable uncertainty as to when that will happen (e.g., Stroeve et al. 2012). Agencies responsible for emergency response and security have documented the need for capabilities that are informed by science (USCG 2013; DOD 2013; U.S. Navy 2014).

During the period of consistent satellite passive microwave observations (1979-present), most numerical models have projected a slower rate of ice loss than the observed rate, with the best-performing models typically including more sophisticated ice processes (e.g., Stroeve et al. 2012). Enhancing understanding and improving predictions of the changing sea ice cover over a range of spatial and temporal scales (hourly, daily, weekly, seasonal, annual, decadal) requires research that addresses the physical properties and processes of the ice itself (e.g., ice thickness, topography, and strength; ice motion and deformation; distribution and properties of snow on ice; and melt pond characteristics). These sea ice characteristics, in turn, are strongly influenced by the atmosphere above and the ocean below the ice. Consequently, it is necessary to take a systems approach that accounts for atmospheric and oceanographic conditions and processes and examines the interactions and feedbacks among the sea ice, atmosphere, and ocean.

The Sea Ice Goal focuses on ice and ocean conditions and processes. Progress in the implementation of the Sea Ice Goal will also contribute to and benefit from research undertaken under the Atmosphere, Marine Ecosystems, Coastal, and Environmental Intelligence Goals. The Sea Ice Goal, and its broader connections to these other components of the Arctic environmental system, also addresses the call for policy-driven research that meets fundamental regional and national needs. For example, the changes that are occurring in the Arctic sea ice cover affect the well-being of Arctic residents (*Well-being*), the functioning of the marine environment (*Stewardship*), regional and national security (*Security*), and potentially regions far beyond the Arctic (*Arctic-Global System*).

Research Objective 3.1. Conduct coordinated/integrated atmosphere-ice-ocean observations and research to understand the processes that determine the spatial and temporal variation of the thickness, extent, and volume of sea ice and their effects on atmosphere-ice-ocean interactions and feedbacks over multiple time scales (hourly, daily, weekly, seasonal, inter-annual, decadal).

Rationale: Sea ice thickness, extent, and volume are key descriptors of the state of the sea ice cover and products of complex interactions and feedbacks in the coupled atmosphere-ice-ocean system. Understanding this system, including the influence of ice on the atmosphere and the ocean, requires a spectrum of coincident observations from a variety of platforms: spaceborne, airborne (manned and unmanned aircraft), surface (ice camps, research vessels, ice-based buoys), and sub-surface (submarines, unmanned underwater vehicles, under-ice profilers and floats, moorings). No single agency operates all of these platforms, nor supports all of the research necessary to understand sea ice thickness, extent and volume over a range of spatial and temporal scales. IARPC Collaborations will be a forum for coordination and integration of atmosphere-ice-ocean observations and process studies, and the data analysis and synthesis necessary to understand the state of the sea ice.

Performance Element 3.1.1: Support investigator-driven observations and process studies of the pack ice (e.g., ice thickness distribution, topography/surface roughness and strength; ice motion and deformation; snow depth distribution and melt pond characteristics; surface albedo and energy balance) and landfast ice (e.g., extent, stability, and break-up).

Lead Agencies: NASA, NSF
Supporting Agencies: DOD (ONR), DOI (BOEM), NOAA

Performance Element 3.1.2: Continue to support the U.S. Interagency Arctic Buoy Program (US IABP) to provide meteorological, ice, and oceanographic data for research purposes and to meet real-time operational requirements. US IABP, coordinated by the National Ice Center and the Polar Science

Center, Applied Physics Laboratory, University of Washington, contributes to the International Arctic Buoy Programme.

Lead Agencies: DHS (USCG), DOD (Navy), NOAA, NSF
Supporting Agencies: DOD (ONR), NASA

Performance Element 3.1.3: Continue Operation IceBridge (OIB) to measure sea ice freeboard and thickness and to measure the depth of snow on the ice in late winter 2017, 2018, and 2019 in the western Arctic Ocean.

Lead Agency: NASA

Performance Element 3.1.4: Launch (1) the NOAA/NASA Joint Polar Satellite System in 2017 to enhance understanding of the sea ice age/thickness, ice concentration, ice surface temperatures, snow cover, and snow water equivalent; and (2) the NASA Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) in 2018 to estimate sea ice thickness over the entire Arctic Ocean and adjacent seas, and in conjunction with the overlapping OIB mission, validate the satellite measurements and the algorithms that convert those measurements into sea ice thickness.

Lead Agencies: NOAA, NASA

Performance Element 3.1.5: Use multiple remote sensing data sets to: (1) investigate sea ice properties and processes and atmosphere-ice-ocean interactions; and (2) develop algorithms for automated ice edge detection and delineation of the marginal ice zone, landfast ice extent, ice classification (e.g., age/type of ice, melt ponds, floe size), and ice motion and deformation.

Lead Agency: DOD (ONR)
Supporting Agencies: DOI (BOEM), NOAA, NASA, NSF

Performance Element 3.1.6: Develop and deploy new technologies that enable persistent data collection on a variety of environmental variables using mobile platforms and sensors operating above, on, in, and under the Arctic sea ice cover to support a framework of observations that will improve forecasting and prediction of sea ice. The Office of Naval Research (ONR) Arctic Mobile Observing System (AMOS) project (FY17-FY21) is an example of a contribution to this performance element.

Lead Agency: DOD (ONR)

Supporting Agencies: DOI (BOEM), NOAA, NASA, NSF

Performance Element 3.1.7: Investigate Arctic Ocean processes, interactions and feedbacks that affect the dynamics and thermodynamics of the sea ice cover, including ocean circulation and stratification, turbulence and mixing, horizontal and vertical heat transport, and freshwater transport and storage. The ONR Stratified Ocean Dynamics of the Arctic (SODA) project (FY16-FY20) is an example of a contribution to this Performance Element.

Lead Agency: DOD (ONR)
Supporting Agencies: DOI (BOEM), NOAA, NASA, NSF

Research Objective 3.2. Improve models for understanding sea ice processes and for enhanced forecasting and prediction of sea ice behavior at a range of spatial and temporal scales.

Rationale: Numerical models are essential tools that complement observations for understanding sea ice processes (e.g., motion and deformation of the ice cover, ice topography and snow depth, and melt ponds that influence the ice thickness distribution). Process models and understanding, in turn, inform the representation of sea ice processes and air-ice-ocean interactions: in large-scale coupled models such as operational models that focus on providing forecasts at short time scales (hourly, daily, weekly); and in Arctic System models used for research to predict the state of the ice over long time scales (seasonal, annual, decadal). No single agency is responsible for sea ice process modeling, operational forecasting, and Arctic System modeling, so IARPC Collaborations offers a forum for bringing together multiple agencies and the sea ice research community. IARPC's implementation structure supports cooperation in improving sea ice process models and large-scale model physics to quantify uncertainty and enhance prediction capability at a range of spatial and temporal scales.

Performance Element 3.2.1: Support investigator-driven modeling studies designed to understand and parameterize key sea ice properties and processes, including ice thickness distribution, topography, and strength; ice motion, deformation and mechanics; snow depth distribution and melt pond characteristics; surface albedo and energy balance; and biogeochemistry.

Lead Agencies: DOD (ONR), NSF
Supporting Agencies: DOE, DOI (BOEM), NOAA, NASA

Performance Element 3.2.2: Enhance operational sea ice forecasting and research-oriented prediction capabilities through improvements to model physics (explicit and parameterized); initialization techniques; assimilation of observations, including newly available and future data sources such as VIIRS, AMSR2, CryoSat-2, SMOS, and ICESat-2; model evaluation and verification; evaluation of model skill, post-processing techniques and forecast guidance tools used in operational forecasts and decision support.

Lead Agency: NOAA
Supporting Agencies: DOD (NRL), DOD (ONR), DOE, DOI (BOEM), NASA, NSF

Research Objective 3.3. Support collaborative networks of researchers and stakeholders, including northern residents, to advance knowledge, understanding, and prediction of the sea ice system.

Rationale: Sea ice research is a diverse field of inquiry. It occurs across multiple spatial and temporal scales, from individual ice crystals and brine pockets to ice floes to ocean basins, and from minutes to years to decades. Sea ice researchers represent many disciplines (e.g., mathematics, physics, geosciences, biological sciences) and use multiple tools and methods (e.g., laboratory investigations, in situ and remote observations, process studies, computer models). The sea ice research community is distributed across multiple sectors (e.g., academe, government, NGOs, private sector) and countries. Collaborative networks will harness such diversity by fostering cooperation and coordination across disciplinary, organizational, and geographic boundaries to advance knowledge, understanding, and prediction of the sea ice system.

Performance Element 3.3.1: Support the Study of Environmental Arctic Change (SEARCH) Sea Ice Action Team to synthesize the results of multiple agencies' and other stakeholders' investments in sea ice observations and process studies and communicate results, information, and the societal implications of sea ice change to broader audiences.

Lead Agency: NSF
Supporting Agency: DOD (ONR)

Performance Element 3.3.2: Support a collaborative network of scientists and stakeholders to advance research on sea ice predictability and prediction at a variety of time and space scales and communicate new knowledge, understanding, and tools to broader audiences.

Lead Agency: NSF
Supporting Agencies: DOD (ONR), DOE, NOAA, NASA

Research Goal 4: Increase Understanding of the Structure and Function of Arctic Marine Ecosystems and Their Role in the Climate System and Advance Predictive Capabilities

In the changing Arctic, improved understanding of marine ecosystem structure and function offers many benefits and is needed to address several IARPC policy drivers. For example, improved ecosystem understanding increases certainty for decision makers charged with environmental stewardship (*Stewardship*). Understanding also advances current predictive modeling capabilities, which better inform management actions and local communities charged with protecting Arctic marine species and their availability for subsistence hunters (*Stewardship, Well-being*). Arctic marine ecosystems appear to be in rapid transition due to the dramatic thinning and loss of sea ice over several decades (Stroeve et al. 2012; Post et al. 2013; Renner et al. 2014; Grebmeier and Maslowski 2014). Understanding these changes and their role in the climate system is crucial to improve the understanding of the Arctic marine ecosystems role as a component of planet Earth (*Arctic-Global Systems*), and cooperation between marine ecosystems researchers and numerous potential collaborators, including northern residents and industry participants, who have particular Local and Indigenous Knowledge of the ecosystems.

Changes in location and timing of seasonal sea ice can have profound and varied effects on pelagic and benthic production, a result of adjusting the transfer of energy from primary producers at the sea surface to the benthos (Bluhm and Gradinger 2008; Moore and Stabeno 2015). A broad ecosystem shift from a benthic- to a pelagic-dominated Arctic marine ecosystem is anticipated at all trophic levels (Grebmeier et al. 2012; Moore et al. 2014), ultimately impacting human communities (Huntington 2009). Marine ecosystems shifts have already begun in the Arctic with observed changes in species distributions of invertebrates (Richman and Lovvorn 2003), fish (Rand and Logerwell 2011), and mammals (Clarke et al. 2013), as well as changes in the size and growth rates of individual animals (von Biela et al. 2011) and the potential for increased gene flow among and between species (Kelly et al. 2010).

The loss of sea ice affects the ability of ice-dependent marine mammals to rest, forage, reproduce, and rear young on ice (Laidre et al. 2015, and references therein) and will change their availability to subsistence hunters. Walrus herds hauled out on land in 7 of the last 9 years, i.e., 2007 to 2015 (C. Jay, personal communication) when the ice edge receded beyond the continental shelf during the autumn ice-minimum (Jay et al. 2012). These events have considerable consequences for population trajectory stemming from increased mortality risks on land (Fay and Kelly 1980; Udevitz et al. 2013). Reduced sea ice has also been associated with limited foraging, declining body condition, and reduced reproduction of polar bears in the southern Beaufort Sea (Rode et al. 2014), as well as impacts to polar bears' major prey—ringed seals—which are threatened by diminishing sea ice (Kelly et al. 2010; Sundqvist et al. 2012; Iacozza and Ferguson 2014).

Impacts of sea ice loss on whales and ice-dependent seals are less clear (Moore and Huntington 2008; Silber et al. 2016), as are the effects of these changes on Indigenous communities that depend on predictable access to such species (Metcalf and Robards 2008).

Feedback processes (e.g., bio-physical relationships) play a fundamental role in the functioning of Arctic ecosystems. Many of these processes are nonlinear in nature, making it difficult to conceptualize or quantify them and therefore to contrast their impact against other feedbacks (Wiese et al. 2013).

Some biotic responses will be difficult to link to physical influences as Arctic food webs are characterized by slow turnover times. Nonetheless, large responses are anticipated given the lower resilience and greater sensitivity to perturbations of Arctic ecosystems—as compared with subarctic (Whitehouse et al. 2014).

The following Research Objectives summarize the next steps while aiming to integrate environmental information through interdisciplinary research and state-of-the-science modeling approaches. Interagency collaborations are required to address the marine ecosystem Objectives as several agencies have complementary and overlapping jurisdictions and knowledge in the marine realm.

Research Objective 4.1. Increase knowledge on the distribution and abundance of Arctic marine species across all trophic levels and scales, including an improved understanding of the formation and maintenance of biological hotspots and proximate causes of shifts in range.

Rationale: An improved understanding of current species' distribution and abundance relative to historical patterns and ongoing changes is a crucial need for decision-making about commercial activities, developing effective plans for conservation, and ensuring that these species remain available for the nutritional and cultural needs of northern coastal Indigenous communities. This effort will benefit from interagency collaboration because of multi-agency jurisdiction of Arctic marine species and the need for agencies to consider impacts to marine resources when planning and authorizing activities in the Arctic. Many of these projects are conducted in collaboration with State, tribal, and Indigenous entities.

Performance Element 4.1.1: Continue distribution and abundance surveys of Arctic marine species, for example, concurrent monitoring of polar bears and their ice seal prey.

Lead Agencies: DOI (FWS), NOAA
Supporting Agencies: DOI (BOEM, USGS), MMC

Performance Element 4.1.2: Continue studies to document Arctic marine species biodiversity (e.g. Arctic Marine Biodiversity Observation Network—AMBON—and programs that monitor loss of sea ice) and habitat use in the Arctic. Ensure datasets will be available through open access data portals.

Lead Agencies: DOI (BOEM, FWS), NOAA
Supporting Agencies: DOD (ONR), MMC, NASA, NSF

Performance Element 4.1.3: Assess winter distributions of key Arctic species, via passive acoustic sampling and satellite tagging for marine mammals to include further development of autonomous, unmanned surface and underwater vehicles equipped with sensors capable of recording marine mammal vocalizations.

Lead Agencies: DOI (BOEM), NOAA
Supporting Agencies: DOI (FWS, USGS), MMC

Research Objective 4.2. Improve understanding of basic life history of Arctic marine species to support multi-agency decision-making.

Rationale: Life history data are fundamental to understanding existing relationships in ecosystems, potential feedback loops, and anticipating biological responses. This effort will benefit from engaging with Indigenous subsistence communities through co-management agreements and community meetings because biological sampling of organisms harvested by subsistence hunters provides efficient and cost-effective access to information that might not be otherwise available to several Federal agencies. Many of these projects are conducted in collaboration with State agencies and nongovernmental collaborators.

Performance Element 4.2.1: Assess feeding ecology of Arctic species and fill seasonal data gaps. One such project will identify walrus prey based on an innovative approach using molecular markers.

Lead Agencies: DOI (BOEM, USGS), NOAA
Supporting Agencies: MMC, NSF

Performance Element 4.2.2: Determine basic life history information on age and growth rates of key links in the food web.

Lead Agencies: DOI (BOEM), NOAA
Supporting Agencies: DOI (USGS), NSF

Performance Element 4.2.3: Assess the value of recent interdisciplinary programs and data synthesis efforts to guide management decisions and allocation of resources.

Lead Agencies: DOD (ONR), DOI (BOEM), USARC
Supporting Agencies: DOI (FWS), NOAA, MMC, NASA

Research Objective 4.3. Advance the understanding of how climate-related changes, biophysical interactions, and feedbacks at different scales in the marine ecosystems impact Arctic marine resources and human communities that depend on them.

Rationale: Predictive, mechanistic relationships linking climate and biological responses will be central to understanding future scenarios and provide decision makers with the best available information. Interdisciplinary research is needed to understand the ways in which key marine species may respond to climate-related changes, such as loss of sea ice. Actions supporting this Objective will build a portfolio of integrated "climate-ready" management actions, tools, and approaches.

Performance Element 4.3.1: Continue Distributed Biological Observatory (DBO)[25] sampling in regions 1-5 and make data publicly available through upload of metadata to the Earth Observing Laboratory/DBO data portal.

Lead Agencies: NOAA, NSF
Supporting Agencies: DOI (BOEM, FWS), NASA

Performance Element 4.3.2: Continue DBO coordination activities including annual workshops, via participation in the Pacific Arctic Group (PAG), and produce the first Pacific Arctic Regional Marine Assessment (PARMA) in 2018.

Lead Agency: NOAA
Supporting Agencies: DOD (ONR), DOI (BOEM), NASA, NSF

Performance Element 4.3.3: Build connections between DBO and existing community-based observation programs and encourage data sharing. For example, the DBO Implementation Plan discusses fostering connections to existing community-based observation programs in an effort to link offshore observations of biological change to local observations and IK.[26]

Lead Agencies: NOAA, NSF
Supporting Agency: DOI (BOEM)

Performance Element 4.3.4: Continue research and make simultaneous observations of biological, chemical, and physical variables to examine linkages among marine species, oceanographic and sea ice conditions, and climate change to understand the mechanisms that affect performance and distribution. Quantify feedbacks and interactions of bottom-up and top-down processes that regulate production. One such project involves investigating the links between bivalve growth and sea ice extent. Several projects require the integration of IK (e.g., the Walrus Adaptability and Long-term Responses: Using multi-proxy data to project Sustainability, or WALRUS, an NSF-BOEM partnership).

Lead Agencies: DOI (BOEM), NOAA, NSF

Supporting Agencies: DOD (ONR), DOI (FWS, USGS), NASA, USARC*Performance Element 4.3.5:* Implement the Regional Action Plan for Southeastern Bering Sea Climate Science[27] and prepare Regional Action Plans for Aleutian Islands and High Arctic Large Marine Ecosystems (LMEs).

Lead Agency: NOAA

Performance Element 4.3.6: Conduct numerical simulations using coupled models to evaluate feedbacks across disciplines and systems.

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[25] See www.arctic.noaa.gov/dbo for more information about the DBO and the location of the regions.

[26] See the decadal DBO Implementation Plan (2015-2024) for more information at http://www.iarpccollaborations.org/uploads/cms/documents/iarpc-dbo-ct-_-dbo-10-year-implementationplan-version1.pdf

[27] Through ecosystem-based fishery management, Alaska Regional Action Plans will provide tools for addressing climate-driven changes to the Bering Sea, Aleutian Islands, and High Arctic LMEs, reducing unintended outcomes of management actions and balancing emergent tradeoffs under climate change. See www.afsc.noaa.gov/news/Regional_action_plan_Bering_Sea.htm for more information.

Lead Agencies: NOAA, NSF
Supporting Agencies: DOD (ONR), DOI (BOEM)

Performance Element 4.3.7: Continue development, testing, and runs of prognostic models that use Intergovernmental Panel on Climate Change (IPCC) scenarios in a regional context to explore current understanding of biophysical interactions and feedbacks, such as perturbations across several modeled food webs from the subarctic to the Arctic to estimate relative ecosystem sensitivities and rates of change. Ongoing efforts in the Bering Sea (i.e., ACLIM) will serve as a pilot program to consider an ensemble approach of multiple model outputs to better understand the impacts of climate change on Arctic LMEs.

Lead Agency: NOAA
Supporting Agencies: DOD (ONR), DOI (USGS), NSF

Research Goal 5: Understand and Project the Mass Balance of Glaciers, Ice Caps, and the Greenland Ice Sheet and Their Consequences for Sea Level Rise

Global mean sea level is estimated to have risen by 1.2 to 1.9 mm per year over the 20th century and that rate rose to 3.0 ± 0.7 mm per year between 1993 and 2010 (Hay et al. 2015). For the period 2003-2009, roughly 25 percent of the observed sea level rise appears to be due to surface mass imbalance of glaciers, excluding those of coastal Greenland and Antarctica (Gardner et al. 2013). This is similar to the contribution from ice sheets, of which roughly two-thirds is derived from Greenland Ice Sheet mass loss (Shepherd et al. 2012).

The increase in the net rate of ice loss from the Greenland Ice Sheet and other Arctic glaciers and ice caps (land ice) stems from warmer air temperatures that escalate melting on ice surfaces, and warmer ocean temperatures that increase calving of icebergs from marine-terminating glaciers. These forcings also modulate the dynamics of the ice, whose motion is governed by gravity and the constraints of surrounding topography. Although significant progress has been made in describing the current state of land ice, key questions remain about the specific processes that add and remove ice in the Arctic System, particularly regarding the interactions of the ice with the atmosphere and ocean. Given the rapidity with which the Arctic is seen to be warming, much may be learned about the future state of Arctic land ice by studying ongoing processes active in subarctic glacier systems.

As land ice and associated icebergs melt, the resultant effects include: contributions of freshwater and nutrients to the coastal zone with direct effects on marine ecosystems (Wadham et al. 2016) and coastal currents (Marsh et al. 2010); increasing storm-induced flooding associated with the rising sea levels (Tebaldi et al. 2012); reduced deep water formation in the ocean with consequences for climate (Weijer et al. 2012); and altered wind fields on various scales.

These effects, particularly those involving sea level rise and altered coastal currents, have regional and global implications. Regionally, the altered coastal currents will impact transport processes, such as spill response and search and rescue operations. Globally, coastal infrastructure, such as municipal gravity-fed sewage systems, subways, ports, military installations, roads, buildings, and property can be damaged by storm surge.

Present estimates of land ice loss rates and sea level rise rates involve large error bars, indicating the need for expanded observation and improved process understanding to allow enhanced modeling and projection over a variety of spatial and temporal scales. These processes are strongly influenced by the atmosphere above, the adjacent or underlying ocean, and the solid earth below the ice. Consequently, it is necessary to take a systems approach that accounts for atmospheric, oceanographic, and solid earth conditions and processes and that examines the interactions and feedbacks among these components.

The Land Ice and Sea Level Goal focuses on land ice conditions and processes and their consequences. Progress in the implementation of this Goal will also contribute to and benefit from research linkages to other aspects of this Plan. This Goal also addresses the call for policy-driven research that meets fundamental regional and national needs. For example, the changes that are occurring in the Arctic land ice cover affect the well-being of Arctic residents, the functioning of the marine environment, regional and national security, and impact and depend upon processes occurring far beyond the Arctic.

Research Objective 5.1. Coordinate and integrate observations to improve understanding of the processes controlling the mass balance of Arctic land ice.

Rationale: Observations of land ice variability and its interactions with the adjacent atmosphere and ocean are necessary to identify the patterns that result from underlying processes, which is the ultimate aim for understanding the system. These observations require the deployment and maintenance of spaceborne, airborne (manned and unmanned aircraft), surface (ice camps, research vessels, ice-based buoys), and sub-surface (unmanned underwater vehicles, under-ice profilers and floats, moorings) platforms. No single agency operates all these platforms, nor supports all the research necessary to understand land ice variability and its contribution to sea level rise. IARPC Collaborations will facilitate coordination and integration of atmosphere-land ice-ocean observations and process studies and the data analysis and synthesis necessary to understand the processes controlling mass balance variability and its consequences. The research activities coordinated to address this Objective also provide the foundation needed for addressing Objectives within the Environmental Intelligence Goal.

Performance Element 5.1.1: Maintain support for aircraft and satellite missions that contribute to long-term observations of land ice, including:

(1) Continue to operate Landsat-8 to monitor changes in the areal extents of Arctic and sub-Arctic glaciers using multispectral imaging to delineate glacier boundaries;

(2) Prepare for the launch of ICESat-2, which will use laser altimetry to infer surface elevation change over Arctic glaciers, ice caps, and the Greenland Ice Sheet;

(3) Continue OIB to ensure adequate overlap with ICESat-2 and allow cross-calibration of the altimetry measurements;

(4) In partnership with the German Aerospace Center (DLR), prepare for the FY 2018 launch of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), to continue measurements of the earth’s gravity field that have been used to infer ice mass loss from Arctic glaciers, ice caps, and the Greenland Ice Sheet;

(5) In partnership with the Indian Space Research Organization (ISRO), continue to develop the NASA-ISRO Synthetic Aperture Radar (NISAR) mission, to measure time-varying displacements of ice-covered surfaces to infer ice flow and extent in Arctic glaciers, ice caps, and the Greenland Ice Sheet.

Lead Agency: NASA
Supporting Agency: DOI (USGS)

Performance Element 5.1.2: Enable the collection of ground-based observations and associated aircraft measurements documenting variability of land ice on a variety of spatial and temporal scales, including:

(1) Support the collection and analysis of observations from networks, such as the Greenland Ice Sheet Monitoring Network (GLISN) to improve estimation of the earth’s structure under Greenland, analysis of deformation within the ice sheet and at its calving margins, and information about glacier dynamics and subglacial geology;

(2) Support the collection and analysis of observations from the Oceans Melting Greenland (OMG) mission to determine how marine glaciers react to the presence of warm, salty Atlantic water;

(3) Support the U.S. Geological Survey (USGS) Benchmark Glaciers Program in Alaska (Gulkana and Wolverine glaciers), which will allow direct comparison of mass balance records from different parts of North America to better understand the response of glaciers to climate changes.

(4) Support the collection and analysis of observations from the Ice2O project in Alaska, which seeks to understand linkages between changes in snowcover and glacier volume and freshwater delivery to the ocean, including impacts on near-shore habitats, coastal currents, marine ecosystems, and local tourism and recreation industries.

Lead Agency: NASA
Supporting Agencies: DOI (USGS), NOAA, NSF

Performance Element 5.1.3: Support investigator-driven studies of land ice process studies across the Arctic, including ocean-glacier interactions, surface and subglacial hydrology, surface mass balance, local surface melt and refreezing, firn densification, glacial isostatic adjustment, iceberg melting, surface energy budget, and related observations.

Lead Agency: NSF
Supporting Agencies: DOI (USGS), NOAA, NASA

Performance Element 5.1.4: Enhance national and international communication and collaboration concerning land ice state and processes, for example, through support of the activities of the SEARCH Land Ice Action Team.

Lead Agency: NSF
Supporting Agency: NASA

Research Objective 5.2. Improve numerical models to enhance projection of ice loss from Arctic land ice and the consequent impact on global sea level and to better understand the predictability of these processes.

Rationale: Numerical and analytical models synthesize understanding derived from observations and process studies. They inform the design of future observations and process studies and enable quantitative projections over various time scales. The IARPC Collaborations will be a forum for cooperation on the improvement of land ice dynamics and mass balance process models and for facilitating the improvement of large-scale model physics to enhance predictive capability at a range of spatial and temporal scales relevant to the missions of the participating agencies. The research activities coordinated to address this Objective also provide the foundation needed for addressing Objectives within the Environmental Intelligence Goal.

Performance Element 5.2.1: Enable the development and assessment of ice sheet models, both as stand-alone models and within the context of earth system models, including:

(1) Continue to develop the Ice Sheet System Model (ISSM), a massively parallelized, multi-purpose finite-element framework to model the mass balance of the Greenland Ice Sheet in the near future and inform future sea level rise projections;

(2) Continue to develop the Community Ice Sheet Model (CISM), a next-generation ice sheet model that serves as the ice dynamics component of the Community Earth System Model (CESM), one of the first global climate models to include coupled, dynamic ice sheets;

(3) Continue to develop ice sheet models within mission-oriented modeling frameworks, such as the Accelerated Climate Modeling for Energy (ACME) project, which will apply an advanced climate and earth system model to investigate the challenges posed by the interactions of climate change and societal energy requirements;

(4) Support the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) to improve projections of sea level via simulations of the evolution of the Greenland Ice Sheet under a changing climate;

(5) Continue to develop and to deploy the Land Ice Verification and Validation (LIVV) Toolkit for the robust evaluation of continental-scale ice sheet models.

Lead Agencies: NASA, NSF
Supporting Agencies: DOE

Performance Element 5.2.2: Develop data sets to be used as boundary and forcing functions for ice sheet, ice cap, and glacier models, including improving regional reanalyses focused on the greater Arctic, improving global reanalysis systems in ways that are relevant to the Arctic, and promoting joint observation-modeling-reanalysis-forecasting activities.

Lead Agency: NASA
Supporting Agencies: DOD (NRL, ONR), NOAA, NSF

Performance Element 5.2.3: Support investigator-driven modeling projects designed to understand and parameterize important land ice processes, including studies of mélange rheologies and dynamics, wet and dry firn processes, meltwater infiltration and refreezing, interactions between the glacier front and subglacial outflow plumes, and basal sliding laws.

Lead Agency: NSF
Supporting Agencies: DOE, DOI (USGS), NASA

Research Goal 6: Advance Understanding of Processes Controlling Permafrost Dynamics and the Impacts on Ecosystems, Infrastructure, and Climate Feedbacks

Permafrost evolution, degradation, and properties influence terrestrial and aquatic ecosystems in Arctic and boreal regions (Bowden et al. 2012; Hinzman et al. 2005; Shur and Jorgenson 2007), impact infrastructure and economies (Walker and Peirce 2015; Larsen et al. 2008), affect human health (Arctic Climate Impact Assessment 2004), and alter global climate via the permafrost carbon feedback (Koven et al. 2015; Schuur et al. 2015). These effects are germane to all of the policy drivers in this Plan: *Well-being*, *Stewardship*, *Security,* and *Arctic-Global System*. Understanding permafrost processes and their dynamic linkages with natural and social systems is important for advancing U.S. policy interests for the 2017-2021 planning period and beyond.

Improved understanding of permafrost dynamics requires an interdisciplinary approach linking biotic, abiotic, and social disciplines in order to consider relevant impacts at local to global scales. Permafrost is a fundamental component of the cryosphere in the northern hemisphere, affecting about 24 percent of the terrestrial landscape (Brown et al 1998). Permafrost is defined as ground that remains at or below 0°C for at least two consecutive years (Van Everdingen 1998). Four zones describe the lateral extent of permafrost regions: continuous (90-100 percent), discontinuous (50-90 percent), sporadic discontinuous (10-50 percent), and isolated discontinuous (< 10 percent). Permafrost zones extend across 80 percent of Alaska. Continuous and discontinuous permafrost underlie 32 percent and 31 percent of the state, respectively, while sporadic permafrost underlies about 8 percent of the state, and isolated discontinuous perfmafrost, an additional 10 percent (Jorgenson et al. 2008). Interactions between climate, topography, hydrology, and ecology operating over long time scales regulate permafrost presence and stability (Shur and Jorgenson 2007). Due to these interactions, permafrost may persist in regions with a mean annual air temperature (MAAT) above 0°C and it may degrade in regions with a MAAT below -10°C (Jorgenson et al. 2010). Since permafrost dynamics are highly integral and influential to Arctic ecosystem processes, an enhanced understanding requires a multi-disciplinary approach that accounts for component couplings.

Permafrost warming, degradation, and thaw subsidence can have significant implications for ecosystems, infrastructure, and climate at local, regional, and global scales (Jorgenson et al. 2001; Nelson et al. 2001; Schuur et al. 2008). In general, permafrost in Alaska has warmed between 0.3°C and 6°C since ground temperature measurements began between the 1950s and 1980s (Romanovsky et al. 2010; Romanovsky et al. 2012). Warming and thawing of near-surface permafrost may lead to widespread terrain instability in ice-rich permafrost regions in the Arctic (Jorgenson et al. 2006; Lantz and Kokeli 2008; Gooseff et al. 2009; Balser et al. 2014; Jones et al. 2015; Liljedahl et al. 2016). Such land surface changes can impact vegetation, hydrology, terrestrial and aquatic ecosystems, and soil carbon dynamics (Grosse et al. 2011; Jorgenson et al. 2013; Kokelj et al. 2015; O'Donnell et al. 2011; Schuur et al. 2008; Vonk et al. 2015). Thawing permafrost also interacts with changes to physical ocean conditions (sea level, storm strength and frequency, and sea ice cover) to influence coastal erosion, which can impact both ecosystems and infrastructure.

The extent and dynamics of permafrost and permafrost-related landscape features remain poorly mapped and modeled at sufficient resolution to predict impacts of climate change along a spectrum of spatial scales, which is essential for adequate understanding driving informed Arctic and global policy. Permafrost properties are linked in complex but quantifiable ways with terrain and ecosystem characteristics (Balser et al. 2015; Jorgenson et al. 2014; Mishra and Riley 2015; Pastick et al. 2014), hydrologic processes and biogeochemistry (Abbott et al. 2014; Hinzman et al. 2006; Walker and Hudson 2003) and disturbance regimes (Gooseff et al. 2009; Mack et al. 2011; Viereck 1973). Because permafrost is a subsurface property, development of geospatial datasets suitable for modeling and scaling typically requires a well-coordinated combination of extensive field work and remote sensing analyses (Cable et al. 2016; Balser et al. 2014; Pastick et al. 2013). Rigorous examination of linkages among disciplines provides the foundation for effective modeling efforts designed to represent permafrost dynamics in local to global systems, to estimate the spatial distribution of permafrost degradation modes (Balser and Jones 2015; Olefeldt 2015; Jones et al. 2015), and to assess the vulnerability of permafrost carbon to quantify potential carbon release to the atmosphere (Schuur et al. 2015; Schuur et al. 2008).

Meeting the Permafrost Goal will require strategic and diligently executed cooperation among Federal agencies with complementary capabilities, programs, and expertise. No single agency can adequately address the gaps in scientific understanding of permafrost dynamics in a changing climate and the required improvements in empirical and modeling research to inform sound Federal policy. Additionally, collaboration with Indigenous organizations and State of Alaska Agencies could further strengthen knowledge exchange and data collection and could inform decisions. Successful development and distribution of actionable knowledge and data will come from linking specific, existing research and management programs housed within laboratories and agencies, as well as promoting and sustaining larger community initiatives and groups (such as NSF's SEARCH Permafrost Action Team and associated Permafrost Carbon Network), which foster synthesis studies across disciplines, provide regular meetings for sharing updates and results, and offer a forum for introduction of new ideas to the larger community. Finally, there is a need for stable, long-term observation networks coordinated across interdisciplinary research efforts and multi-agency approaches.

Research Objective 6.1. Improve understanding of how climate, physiography, terrain conditions, vegetation, and patterns of disturbance interact to control permafrost dynamics.

Rationale: Permafrost distribution and degradation are controlled by complex interactions among physical and biological factors that are heterogeneous across the landscape and are only partially understood. Warmer air temperatures are increasing permafrost temperature and thaw in many areas, changing hydrology, and influencing vegetation composition. Fire and thermokarst disturbances also affect thaw and may lead to more abrupt landscape changes. Permafrost thaw will likely increase risks to critical infrastructure in the Arctic, especially in the discontinuous permafrost zone, and will pose new challenges for residents, while contributing to ecosystem and global climate shifts. Through enhanced monitoring and research focused on improved understanding of the controls on permafrost dynamics, composition and distribution, anticipated environmental change and infrastructure damages due to thawing permafrost may be better quantified, thereby reducing risks locally and globally.

Performance Element 6.1.1: Continue to conduct and coordinate monitoring and modeling of permafrost temperature across a wide range of terrain units and climatic zones and to use obtained data to refine relationships between the ground thermal regime of shallow and deep permafrost and terrain properties.

Lead Agency: NSF
Supporting Agencies: DOD (USACE), DOE, DOI (NPS, USGS), USDA (NRCS), NOAA, NASA

Performance Element 6.1.2: Conduct field-based research that examines and quantifies relationships among surface topography, vegetation composition, hydrology, disturbance effects (including fire and thermokarst), and geophysical processes in permafrost soils to feed directly into models, decision support tools, and predictive analyses.

Lead Agencies: DOD (USACE), DOE, NSF
Supporting Agencies: DOI (NPS, USGS), NASA

Performance Element 6.1.3: Support field-based research to improve understanding of how changes to Arctic lake and river ecosystems affect permafrost stability, water availability, and habitat provision, with a particular focus on wintertime ice regimes.

Lead Agency: NSF
Supporting Agencies: DOI (BLM, FWS, NPS, USGS), NASA

Performance Element 6.1.4: Integrate field, laboratory, and remote sensing information to map local, regional, and global permafrost-influenced landscape dynamics and their impact on vegetation, hydrology, terrestrial and aquatic ecosystems, and soil carbon dynamics in the Arctic. Develop spatially-explicit decision support systems and predictive tools.

Lead Agencies: DOD (USACE), DOE, DOI (BLM)
Supporting Agencies: DOI (FWS, NPS, USGS), NOAA, NASA, NSF

Performance Element 6.1.5: Support activities, including the SEARCH Permafrost Action Team, to foster continued efforts to link multi-agency investments while expanding empirical datasets and synthesizing information that will inform the development of an updated permafrost ground ice content map for Alaska.

Lead Agency: NSF
Supporting Agencies: DOD (USACE), DOE, DOI (BLM, FWS, NPS), NOAA, NASA

Research Objective 6.2. Improve and expand understanding of how warming and thawing of permafrost influence the vulnerability of soil carbon, including the potential release of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere.

Rationale: Permafrost contains vast quantities of earth's soil organic carbon stocks—twice as much as the current atmospheric pool, which may be decomposed and released as greenhouse gases (including CO_2 and CH_4) when permafrost soils thaw. This carbon increases atmospheric greenhouse gas concentrations and contributes to further warming, with regional and global climate impacts. The amount of carbon that could be released from thawing permafrost is dependent on multiple factors, and remains very difficult to quantify, yet is an essential consideration across multiple scales for projecting future climate change. Improved understanding of the vulnerability of permafrost carbon to decomposition and the potential magnitude of carbon release will improve both empirical and modeling efforts designed to identify and quantify how permafrost thaw will impact climate, ecosystems, and society.

Performance Element 6.2.1: Support field-based research and monitoring focused on quantifying the key processes controlling soil carbon cycling at northern latitudes and potential carbon release to the atmosphere, including temperature and hydrological effects.

Lead Agency: NSF
Supporting Agencies: DOD (USACE), DOE, DOI (BLM, FWS, NPS, USGS), NASA

Performance Element 6.2.2: Support research to improve scaling methods for estimating CO_2 and CH_4 emissions from the permafrost region (including that which is conducted by the SEARCH Permafrost Action Team) to link multi-agency investments in soil carbon research that culminates in synthesis publications.

Lead Agency: NSF
Supporting Agencies: DOD (USACE), DOE, NOAA, NASA

Performance Element 6.2.3: Utilize empirical, multi-scale approaches to make spatially-explicit estimates of vulnerability of permafrost carbon and release of both CO_2 and CH_4.

Lead Agency: DOE
Supporting Agencies: DOD (USACE), DOI (USGS), NASA

Performance Element 6.2.4: Utilize empirical, multi-scale approaches to make spatially explicit estimates of the potential extent and modes of abrupt permafrost thaw, including thermokarst and cryogenic landslides, and of the downstream effects of these events on microbial processes and carbon fluxes.

Lead Agency: DOD (USACE)
Supporting Agency: DOI (USGS), NSF

Performance Element 6.2.5: Better understand the rate of subsea permafrost degradation and its role in methane gas hydrate decomposition and feedbacks to the climate system. Develop estimates of contributions to atmospheric carbon from subsea permafrost sources at present and under future scenarios.

Lead Agency: DOI (USGS)
Supporting Agencies: DOI (BOEM), NOAA, NSF

Research Objective 6.3. In collaboration with efforts described under the Terrestrial Ecosystems Goal, continue to improve integration of empirically measured permafrost processes into models that predict how climate change, hydrology, and ecosystem shifts and disturbances interact within terrestrial and freshwater aquatic systems to impact permafrost evolution, degradation, and feedbacks from local landscapes to the circum-Arctic.

Rationale: The ability to estimate circumpolar impacts of permafrost thaw and to predict changes to ecosystem structure and function across regions is central to predicting global change. At present, the ability to estimate these impacts is severely hampered by limitations in modeling and scaling capabilities for permafrost processes across diverse landscapes. The complex, multi-factorial nature of permafrost processes within the context of ecosystems drives the need for linking empirical measurements with model functions and parameters to benchmark the models. Improved predictive accuracy and understanding of permafrost/ecosystem process dynamics will directly enhance the ability to predict global climate shifts and anticipated shifts in ecosystem structure and function from local to continental scales.

Performance Element 6.3.1: Conduct field-based research and monitoring needed to improve understanding of the linkages between key terrestrial ecosystem processes and permafrost properties and to incorporate empirical information into modeling efforts at various scales.

Lead Agencies: DOE, DOI (FWS), NSF
Supporting Agencies: DOD (USACE), DOI (BLM, NPS, USGS), USDA (USFS), NASA

Performance Element 6.3.2: Carry out research to quantify and integrate across scales, the effects of warming permafrost on ecosystem processing related with disturbance regimes, including fire, thermokarst, and landscape changes.

Lead Agency: DOI (FWS, USGS), NSF
Supporting Agencies: DOD (USACE), DOI (BLM, NPS), USDA (USFS), NASA

Performance Element 6.3.3: Facilitate and harmonize the production of key geospatial datasets from extensive field measurements, remotely-sensed, and other data sources needed for model initialization, calibration, and validation. Organize and host workshops to enable this activity across agencies engaged in data development with attention to data congruity and scalability.

Lead Agencies: DOI (BLM, FWS), NASA
Supporting Agencies: DOD (USACE), DOE, DOI (NPS), NSF

Performance Element 6.3.4: Support continued development of robust modeling tools and approaches to integrate models of ecosystem processes at various scales since permafrost dynamics are integral to these processes and vice-versa. Facilitate this activity through workshops that foster interagency information exchange, engagement, and data development with attention to data congruity and scalability to produce products accessible to multiple agencies.

Lead Agency: DOE
Supporting Agencies: DOD (USACE), DOI (BLM, NPS), NOAA, NASA, NSF

Research Objective 6.4. Determine how warming and thawing permafrost impacts infrastructure and human health.

Rationale: Thawing of ice-rich permafrost and melting of massive ground ice bodies causes terrain subsidence. This subsidence can result in extensive and costly damage to critical infrastructure and create new risks for northern residents. Across much of the Arctic where transportation infrastructure is not duplicated, damages could cut off easy access to communities. Permafrost warming and thaw can also impact human health through release of dissolved organic carbon or biological and chemical contaminants into drinking water supplies, through disruption of sewage collection and disposal systems, and through alteration of water drainage patterns in communities.

Performance Element 6.4.1: Survey Federal research agencies and non-Federal partners/stakeholders on their use of tools, methods, and means to monitor changes in landscape conditions due to changes in permafrost with a focus on hazards to infrastructure and health. Develop, enhance, and update "Best Practices" guides for mitigation of impacts to building foundations and other infrastructure.

Lead Agency: DOI (BLM)

Supporting Agencies: DOD (OSD, USACE), DOI (BIA), HHS, Denali Commission, EPA

Performance Element 6.4.2: In collaboration with relevant Indigenous organizations, survey local communities and regional agencies—those which maintain infrastructure and monitor health—on the impacts of warming and thawing permafrost. Integrate these responses within a document characterizing and summarizing overall impacts of warming and thawing permafrost.

Lead Agencies: DOD (OSD), Denali Commission
Supporting Agencies: DOD (USACE), DOI (BLM), HHS, NOAA, EPA

Research Goal 7: Advance an Integrated, Landscape-scale Understanding of Arctic Terrestrial and Freshwater Ecosystems and the Potential for Future Change

Arctic terrestrial and freshwater ecosystems are rapidly changing in response to a variety of forcing factors, including a changing climate, alterations in natural disturbance regimes, and human-caused perturbations (Bernhardt et al. 2011; Bunn and Goetz 2006; Chapin et al. 2010; Epstein et al. 2010; Hill and Henry 2011; Johnstone et al. 2010; Jorgenson et al. 2010; Kim et al. 2012; Myers-Smith et al. 2006, 2011). In turn, these environmental changes are altering a number of important goods, services, and other contributions Arctic ecosystems provide to society, including critical plant and animal populations and their habitats, biotic resources essential to subsistence lifestyles and cultures, and feedbacks to regional and global climate systems (Joly et al. 2006; Kofinas et al. 2010; Noel et al. 2004; Tape et al. 2016). Of particular interest are the broader impacts of ongoing changes to the natural fire regime (Higuera et al. 2008; Jones et al. 2013; Kasischke et al. 2010; Kelly et al. 2013), the potential feedback of these changes to climate (Kasischke and Hoy 2012; Mack et al. 2011; Randerson et al. 2006; Rocha et al. 2012), and impacts on the health and well-being of Arctic residents (Yue et al. 2015). Continuing investment to improve understanding of the causes and consequences of changes to terrestrial and freshwater ecosystems provides needed information for all four IARPC policy drivers, as they are a key component of the Arctic environment (*Stewardship and Security*), provide important feedbacks to the climate (*Arctic-Global System*), and provide key ecosystem services that contribute to the health and well-being of Arctic residents (*Well-being*).

A wide range of ongoing research, inventory, and monitoring activities across Federal agencies in the Arctic focuses on understanding how ecosystems and humans are responding to recent environmental changes. In many cases these activities are being carried out to address priority management needs. Understanding how the growing extent and intensity of environmental changes will impact Arctic ecosystems and societies requires continued and expanded research in three areas:

(1) Understanding of and ability to model feedbacks and interactions among causes of environmental change and the responses of terrestrial and freshwater ecosystems, particularly hydrologic, permafrost, and disturbance dynamics;

(2) Knowledge of how changes to ecosystems alter animal and plant populations and subsistence opportunities;

(3) Evaluation of the effects of changing fire regimes on rural and urban communities and atmospheric carbon budgets and other climate feedbacks.

The Terrestrial Ecosystems Goal will facilitate the improvement of important process modeling activities currently being supported by a range of Federal agencies through its focus on research that includes long-term monitoring activities, collection and analysis of field-based observations for specific projects, and creation of geospatial data products, especially from airborne and spaceborne remote sensing data. These agencies are also conducting critical monitoring and research activities to understand the impacts of ecosystem changes to ecosystem services.

The three Research Objectives for this Goal and the Performance Elements identified for them provide a framework for coordinating Federally sponsored research and monitoring activities. The Performance Elements are based upon extensive, longer-term research, inventory, and monitoring activities supported by Department of the Interior bureaus (Bureau of Land Management, Fish and Wildlife Service, USGS, National Park Service, Bureau of Indian Affairs), U.S. Department of Agriculture bureaus

(U.S. Forest Service, Natural Resources Conservation Service), NSF, and a number of shorter-term research activities sponsored by these and other Federal agencies (DOD, DOE, NASA). The Performance Elements also incorporate opportunities for coordination, integration, and synthesis of research across agencies, including activities to support the Arctic Council, the Department of Energy's Next Generation Ecosystem Experiment-Arctic (NGEE), the Department of the Interior's Alaska Climate Science Center, Landscape Conservation Cooperatives (LCCs), and North Slope Science Initiative (NSSI), the Joint Fire Science Program's Alaska Fire Science Consortium, NASA's Arctic-Boreal Vulnerability Experiment (ABoVE), NOAA's Alaska Center for Climate Assessment and Policy (ACCAP), and NSF's SEARCH Permafrost Action Team. This latter group of projects and programs include significant interactions with key State of Alaska agencies, including the Departments of Natural Resources and Fish and Game. From an international perspective, research and monitoring activities that address the Terrestrial Ecosystems Goal are being coordinated through the activities of the Arctic Council as well as agreements between U.S. and Canadian Federal agencies.

Research Objective 7.1. Improve understanding of and ability to model feedbacks and interactions among the large-scale processes causing change (climate, natural disturbances, and human-caused perturbations) and the responses of terrestrial and freshwater ecosystems.

Rationale: This Objective will focus on continuing and expanding observations, monitoring, and research to understand how variations in climate, disturbances, and human-caused perturbations are causing changes to terrestrial and freshwater ecosystems. These scientific activities not only focus on landscape-scale composition, structure, and function, but also on flora, fauna, permafrost, and hydrology dynamics, and above- and below-ground carbon reservoirs. This research is also directed toward understanding how changes to ecosystems induce feedbacks to climate and disturbance regimes. Together, this group of activities provides the basis for improving regional and global scale ecological and earth science models, as well as coupled climate-ecosystem models that incorporate key disturbance processes, in particular wildland fire. The research activities that would be coordinated to address this Objective also provide the foundation needed for addressing the other Objectives within the Permafrost Goal.

Performance Element 7.1.1: Carry out and synthesize results from field-based research and monitoring needed to improve understanding of important ecosystem processes and feedbacks, including their responses to environmental changes.

Lead Agencies: DOI (FWS, USGS), NSF
Supporting Agencies: DOE, DOI (BLM, NPS), USDA (NRCS, USFS), NASA

Performance Element 7.1.2: Carry out and synthesize research on and monitoring of the disturbance processes responsible for changes to key landscapes, including fire, warming permafrost, insects and pathogens, and human activities.

Lead Agencies: DOI (BLM), NASA, NSF
Supporting Agencies: DOD (USACE), DOE, DOI (FWS, NPS, USGS), USDA (USFS)

Performance Element 7.1.3: Facilitate and harmonize the production, integration, and distribution of key geospatial datasets from remotely-sensed and other data sources that are needed for monitoring key ecosystem processes and landscape changes and for model initialization, calibration, and validation.

Lead Agency: NASA
Supporting Agencies: DOE, DOI (BLM, FWS, NPS, USGS)

Performance Element 7.1.4: Improve existing and develop advanced models for integrating climate, disturbance, above- and below-ground dynamics and interactions and feedbacks to characterize and predict Arctic landscape and ecosystem change.

Lead Agency: DOE, NSF
Supporting Agencies: DOI (BLM, FWS, NPS, USGS), NASA

Research Objective 7.2. Advance understanding of how changes to ecosystems alter animal and plant populations and their habitats and subsistence activities that depend on them.

Rationale: Terrestrial and freshwater ecosystems are important for subsistence and the culture of Arctic residents. These ecosystems provide key habitats for a number of plant species, and resident and migratory fish and terrestrial animal species unique to Arctic regions. These species and their ecosystems also provide the basis for important subsistence activities that are central to the lifestyles and well-being of many northern residents, especially Indigenous communities. This Objective will focus on continuing and expanding the science programs needed to understand how changes to terrestrial and freshwater ecosystems are influencing plant, fish, and terrestrial animal populations and habitats, and how these changes impact human uses of these resources. The activities for the Terrestrial Ecosystems Goal need to include engagement of key stakeholder groups in order to incorporate IK and LK. The research activities coordinated to address this Objective also provide the foundation needed for addressing Objectives within the Health and Well-being Goal.

Performance Element 7.2.1: Coordinate the development of maps from remotely-sensed data and synthesize available data to document changing plant, fish, and terrestrial animal populations and their habitats.

Lead Agencies: DOI (FWS, USGS)
Supporting Agencies: DOI (BLM, NPS), NASA

Performance Element 7.2.2: Compare trends in aquatic and terrestrial animal populations and movements with changing patterns of vegetation cover, lake, pond, and wetland extent and characteristics to determine whether and how shifting habitats are influencing animal behaviors and population dynamics.

Lead Agency: DOI (FWS)
Supporting Agencies: DOI (BLM, NPS, USGS), NASA, NSF

Performance Element 7.2.3: Incorporate scientific observations and the perspectives of IK and/or LK knowledge holders into assessments of how changing Arctic ecosystems, flora, and fauna are affecting important subsistence activities, lifestyles, and well-being of northern residents.

Lead Agency: DOI (FWS)
Supporting Agencies: DOI (BIA, BLM, NPS, USGS), NASA

Research Objective 7.3. Evaluate how changes in fire activity are impacting rural and urban communities, atmospheric emissions and carbon budgets, and other feedbacks to climate.

Rationale: Fire is a primary disturbance agent for terrestrial ecosystems in northern regions and is included as a critical cause of landscape change for the scientific activities covered in Objectives 7.1 and 7.2. In addition, the effects of changes in timing, size, area burned, and intensity of fires are impacting rural and urban communities throughout much of the North. Fires can cause loss of life and property, negatively impact air quality, and alter availability of subsistence resources. Shifts in fire regimes may also influence terrestrial and atmospheric carbon dynamics, with the potential to impact climate at regional and global scales. The Performance Elements that are part of this Objective would continue activities that are part of ongoing IARPC Collaborations. The research activities coordinated to address this Objective also provide the foundation needed for addressing Objectives within the Atmosphere Goal.

Performance Element 7.3.1: Evaluate how changing fire regimes have and are likely to impact northern communities, via impacts to infrastructure, health, and subsistence opportunities.

Lead Agency: DOI (BLM)
Supporting Agencies: DOI (BIA, FWS, NPS, USGS), USDA (USFS), NASA, NSF

Performance Element 7.3.2: Coordinate research on the observations, geospatial dataset generation, and model improvement needed to estimate emissions from wildland fires and the potential for those emissions to affect atmospheric carbon budgets and climate feedbacks.

Lead Agency: NASA
Supporting Agencies: DOI (BLM, FWS, NPS, USGS), USDA (USFS), NSF

Research Goal 8: Strengthen Coastal Community Resilience and Advance Stewardship of Coastal Natural and Cultural Resources by Engaging in Research Related to the Interconnections of People, Natural, and Built Environments

For a number of reasons, research on Arctic coastal areas is particularly complex and cross-cutting. Coastal areas comprise the nexus of marine, terrestrial, and freshwater systems and are home to the majority of Arctic human communities. Arctic coastlines are already experiencing climate change impacts such as flooding and coastal erosion, including some of the highest shoreline erosion rates in the United States: most of Alaska's northern coast is retreating at rates of more than 1m per year (Gibbs and Richmond 2015).

Many issues specific to the Arctic coastal zone are related to human coastal communities: culture, food security, safety, increased commercial activity, infrastructure, biodiversity, and physical and biological processes. To provide the critical knowledge required to navigate decision-making and to inform policy regarding this distinctive geography, research on the interconnections between Arctic people and their natural and built coastal environments is necessary. Thus, Arctic coastal areas offer rich research opportunities at the confluence of social, engineering, and biological and physical sciences. Understanding gained from the research will advance *Well-being*, S*tewardship*, and *Security* in the region.

Already, research coordination among multiple groups is taking place from local to international scales, and the Coastal Goal builds on and strengthens that work. Under the U.S. Chairmanship of the Arctic Council, the Federal government has been leading an international effort with multiple collaborators, including groups that represent Indigenous coastal communities, to build a framework for resilience to rapid changes in the Arctic. Research into coastal physical processes, coastal inundation, and improved mapping data will support the work of the Denali Commission, which is working with the Arctic Executive Steering Committee Community Resilience Working Group to facilitate relocation of coastal villages, necessitated by considerable coastal erosion and increased storm surges in Alaska. Phenology and biodiversity monitoring and modeling research will strengthen scenarios to help identify future research and monitoring needs undertaken by State-Federal partnerships such as NSSI. The Alaska Climate Change Executive Roundtable (ACCER), which regularly discusses the role of science in understanding the ecological impacts of climate change to the built environment, will benefit from research into physical coastal processes and enhanced observational data. Additionally, LCCs in Arctic coastal areas are actively engaging communities in research by convening workshops to learn about issues impacting their landscapes and to support community-based monitoring.

All steps of research—developing priorities and deliverables, designing projects, conducting research, disseminating results, and collaborating on deliverables—benefit from engaging community members. Collaboration and engagement enable meaningful research among community members, IK holders, LK holders, and interagency researchers. The process of sharing research results with communities using approaches compatible with the needs and wants of the community is a critical aspect of building community engagement.

Research Objective 8.1. Engage coastal communities in research to advance knowledge on cultural, safety, and infrastructure issues for coastal communities.

Rationale: More information is needed to develop the strategies necessary for coastal communities to adapt to environmental, social, and economic changes in the coming years and decades. The majority of people in the U.S. Arctic live in coastal areas where resources traditionally have been available throughout the seasons; as a result, planning and providing research findings on the sustainable economic development of coastal areas in a time of rapid change is an area of crucial focus. When engaging in research in Arctic coastal areas, it is informative, productive, and respectful to work with community members, IK holders, and LK holders, throughout the project—i.e., from project conception to communication of results. Coastal areas are also poised to participate in community-based monitoring programs that enable people to report changes and other information to researchers and to participate in research about the places where they live. Further, due to rapidly changing climate, physical, and biotic systems in Arctic coastal areas, efforts to document cultural artifacts and create tools to assist with modeling for planning, protect-in-place strategies, and emergency response become crucial activities that must be addressed in a timely fashion.

Performance Element 8.1.1: Engage coastal community members in research by seeking cooperative opportunities between community members, IK holders, and/or LK holders, and researchers in knowledge co-production research processes. Employ IK and/or LK to jointly conceive of and plan research activities and to report research results back to communities.

Lead Agencies: DOI (BLM, BOEM, FWS), EPA, NOAA, NSF
Supporting Agencies: DHS, DOI (NPS, USGS)

Performance Element 8.1.2: Engage coastal community members in research by supporting community-based monitoring focused on measuring physical and biotic information by strengthening initiatives led by groups such as the Arctic-focused LCCs, BOEM, NOAA, and FWS.

Lead Agencies: DOI (BOEM, FWS), NOAA
Supporting Agency: NSF

Performance Element 8.1.3: Support economic development research for the sustainable development of resilient communities. For example, create comprehensive economic planning strategies by DOC Economic Development Administration (EDA) planning grantees in Alaska coastal communities.

Lead Agency: DOC (EDA)
Supporting Agency: NSF

Performance Element 8.1.4: Investigate and protect cultural resources through research to identify and document archaeological sites in high-risk, rapidly eroding Arctic coastal areas.

Lead Agencies: DOI (BLM, NPS)
Supporting Agency: NSF

Performance Element 8.1.5: Advance the understanding of storm surge and saline inundation impacts on infrastructure and human safety. Multiagency partners include the Alaska Department of Geological and Geophysical Surveys and the ACCER.

Lead Agency: NOAA
Supporting Agency: DOD (USACE)

Research Objective 8.2. Advance knowledge of ecosystems and environmental health in coastal areas by monitoring trends and modeling biological processes.

Rationale: Monitoring species status and trends and increasing understanding of biological processes advances natural resources stewardship and thus helps maintain biodiversity in Arctic coastal areas. Understanding mechanisms and conditions of coastal invasive species and wildlife disease creates options for management. Informed hunt, harvest, and conservation management is beneficial to advancing stewardship of natural resources.

Performance Element 8.2.1: Monitor and conduct studies to understand trends, processes, and biotic-abiotic feedback loops affecting the distribution, abundance, and ecology of coastal species in relation to food security, biodiversity, and ecosystems through projects such as the Arctic Council Conservation of Arctic Flora and Fauna working group Coastal Biodiversity Monitoring Programme.

Lead Agencies: DOI (BOEM, USGS), NOAA
Supporting Agencies: DOI (BLM, FWS, NPS), MMC

Performance Element 8.2.2: Develop ecological modeling capabilities to understand issues related to the coastal Arctic. Develop online eco-informatics tools such as Coastal Biodiversity Risk Analysis Tool (CBRAT) for Arctic coastal areas to deliver, at a regional scale, predicted relative vulnerability of coastal species and ecosystems to climate change, including temperature increases, sea level rise, and ocean acidification.

Lead Agency: EPA

Performance Element 8.2.3: Continue to develop a general Arctic-wide wildlife response model that relates to species-specific models of Arctic coastal organisms.

Lead Agency: DOI (USGS)

Performance Element 8.2.4: Understand and monitor processes to manage and mitigate potential and realized threats from coastal invasive species, biotoxicoses, and wildlife diseases by leveraging research under initiatives and programs such as One Health, the DBO network, AMBON, and Aerial Surveys of Arctic Marine Mammals (ASAMM) work.

Lead Agencies: HHS, NOAA
Supporting Agencies: DOI (BOEM, FWS, USGS), MMC

Performance Element 8.2.5: Conduct research that informs changes in wildlife hunt, harvest, and conservation management such as the Arctic-related LCC-funded moose sightability correction factor model development effort.

Lead Agency: DOI (FWS)
Supporting Agency: NOAA

Performance Element 8.2.6: Improve knowledge of phenology in relation to coastal climate and plant and animal life to better understand issues related to mismatches between prey, predators, hunters, and gatherers in the context of and in collaboration with Arctic coastal communities. This element includes a Western Alaska LCC-funded project on subsistence berry availability.

Lead Agencies: DOI (FWS, USGS)
Supporting Agency: NSF

Research Objective 8.3. Advance knowledge of the physical coastal processes impacting natural and built environments.

Rationale: Changes in climate are affecting physical coastal processes, with potential significant threats to infrastructure, food security, and biodiversity. Coastal erosion is leading to property and habitat loss, threatening the existence of coastal communities in their current physical locations. Increased storm surge and inundation of low-lying areas imperil some coastal communities. Changes to hydrology affect availability of freshwater, as well as food sources such as fish. Changes in the timing of physical conditions (e.g. sea ice loss, precipitation, water temperature) and biological conditions (e.g. plankton blooms, prey migration) are creating mismatches between prey, predators, and hunters, affecting both wildlife and humans.

Performance Element 8.3.1: Improve understanding of coastal erosion and deposition, including related geomorphic changes due to permafrost degradation, reduced sea ice extent, storm surge, increased wave action, and sea level rise. This Element includes work by the USGS Coastal and Marine Geology Program, USGS Alaska Science Center, U.S. Army Corps of Engineers (USACE), and others.

Lead Agencies: DOD (USACE), DOI (USGS)
Supporting Agencies: DOI (BOEM), NOAA, NSF

Performance Element 8.3.2: Increase understanding of coastal freshwater hydrologic changes in rivers, lakes, snow, and permafrost through projects such as the Soil Climate Analysis Network (SCAN) soil moisture and temperature site monitoring.

Lead Agencies: DOI (USGS), NOAA, USDA (NRCS)
Supporting Agencies: DOI (BLM, BOEM, NPS), NASA, NSF

Research Objective 8.4. Improve observations, mapping, and charting to support research across the coastal interface.

Rationale: To support the decisions community, State, and Federal governments need to make from local to international levels, robust environmental intelligence on past conditions, current trends, and future projections is imperative. Thus, accurate observations, mapping, and charting data must be available for modeling and analysis across the entire coastal area. To support data collection, new sensors and technologies are needed for observations year-round in Arctic coastal conditions and geographies.

Performance Element 8.4.1: Update the National Spatial Reference System in the Arctic to enable integration of baseline geospatial datasets in coastal areas to support research and predictive capabilities across the coastal interface.

Lead Agency: NOAA
Supporting Agency: DOD (NGA)

Performance Element 8.4.2: Develop new sensor technologies and data collection and application methods specific to understanding and characterizing relationships within coastal systems across all seasons for natural resource, community, and emergency response planning and management. For example, support implementation of an integrated coastal and near-coastal water level sensor network, including developing and piloting sensor technologies for use in year-round water level observations.

Lead Agency: NOAA
Supporting Agencies: DOI (NPS, FWS)

Performance Element 8.4.3: Produce modeled tidal predictions for the U.S. Arctic. Involve multiagency collaborators, including Alaska Ocean Observing System (AOOS) representatives.

Lead Agency: NOAA

Research Goal 9: Enhance Frameworks for Environmental Intelligence Gathering, Interpretation, and Application toward Decision Support

To adequately support decision-making in the face of unprecedented change in the Arctic, the United States and its international partners need improved scientific data collection and stewardship, understanding, and environmental predictions. This challenge requires frameworks for generating Environmental Intelligence: *integrated environmental knowledge that is timely, reliable and suitable for the decisions at hand.*

Developing suitable Environmental Intelligence frameworks requires the integration of two distinct aspects of research. The first concerns the **end-to-end** integration of research across the linked and iterative steps of problem identification, environmental observing, understanding, prediction, and decision support. For example, safe marine transit through Arctic waters requires engagement with operators to understand the details of their information needs, such as high resolution sea ice forecasts. To produce these forecasts, sparse yet detailed observations of sea ice from drifting ice buoys, community-based observers, and other *in situ* observations must be synthesized with broad, low-resolution satellite observations. Synthesized observations must then be assimilated into forecast models, which subsequently must be tested and validated through efforts like observational process studies—feeding back into an iterative cycle of improved observing and modeling capabilities.

The second aspect of Environmental Intelligence requires integration of research across the components of the **Arctic System**, as most decision-making contexts require a holistic view. Building on the example in the previous paragraph, research is needed to inform how gridded estimates of sea ice thickness are interdependent with weather systems and ocean currents. With its emphasis on understanding the interconnected nature of the Arctic, IK presents a model for Arctic System integration.

Interagency collaboration is ideal for making progress on both **end-to-end** and **Arctic System** integration, because capacities and mission mandates to provide decision support tend to be distributed across many institutions and independently sponsored work. For example, NOAA and the Department of the Interior (DOI) sponsor many Alaska-based programs directly concerned with research for stakeholder engagement and decision support, such as ACCAP, AOOS and FWS's LCCs. These agencies and others like NSF, DOE, and NASA also support sustained observing of the Arctic environments; DOE, NSF, NASA, ONR, and NOAA all contribute to models for improved predictions and projections, and many agencies support data centers that contribute comprehensive data stewardship for valuable Arctic data products. The Arctic Domain Awareness Center (ADAC), sponsored by DHS, bridges between research and operations to improve maritime domain awareness in support of the U.S. Coast Guard's (USGC) mission. IARPC Collaborations will serve as a valuable forum for sharing practices and linking capabilities across IARPC agencies and outside collaborators.

While these efforts in the Arctic provide a solid foundation of knowledge and expertise, the Environmental Intelligence Goal addresses key areas for interagency progress. The sparseness of observational coverage and limited year-round environmental intelligence gathering have hobbled efforts to fully understand the impacts of changing environmental conditions on global processes as well as weather patterns, ecosystems, economic development, and safety. Interagency collaboration can leverage sparse observing assets and propel enhancements through the development of autonomous technologies (Research Objective 9.1). Modeling is a vital tool to advance system integration, to capture feedbacks within the systems, and to extend current understanding into the future. Progress is needed on how Arctic-specific processes and feedbacks are represented in models (Research Objective 9.2). Further, Arctic modeling can benefit from global and regional improvements to things like model resolution, as well as from comparative assessments, including quantified uncertainties among models (Research Objective 9.3). Arctic data stewardship, sharing, and access is evolving from systems where data are discovered in data catalogues and downloaded to the local machines of users, to a system of distributed data nodes with visualization and collaboration platform capabilities made to enable interoperability. Interagency collaboration is needed to understand the connection between these distributed nodes and work toward common visions (Research Objective 9.4) for exchanging and integrating data, in particular across disciplines. Finally, the practices of and frameworks for exchanging knowledge between researchers and stakeholders are in an exciting and dynamic growth period, yet few organizations have the capacity or mandate to adequately address the needs. IARPC Collaborations can serve as a valuable forum for advancing dialog on engagement research, decision support, and science communications (Research Objective 9.5) and feedback critical areas for progress (e.g. specific data needs) to the other Research Objectives in this Goal.

Improvements within and across each of these areas will improve the ability to understand, communicate about, and support decisions in response to the impacts of Arctic change. These efforts, across the scales from community to global at which IARPC agencies engage, support each policy driver of this plan *(Well-being, Stewardship, Security, Arctic-Global Systems)*.

Research Objective 9.1. Enhance multi-agency and outside collaborators participation in new and existing activities to improve best practices, coordination, and synthesis of Arctic observations toward a fully integrated interagency U.S. Arctic Observing Network (U.S. AON).

Rationale: U.S. Arctic observational systems have advanced considerably in their coordination since the International Polar Year and many efforts can be considered regional or thematic building blocks toward a U.S. AON. Sustaining support for and enhancing multi-agency participation in these activities is vital, as is fostering the formation of new efforts. Further, there remains considerable work to forge connections across these typically disciplinary efforts toward a system of observations. In addition to coordinating Federal agency efforts, the U.S. AON will foster coordination with collaborators in the State of Alaska, community-based observing networks, and collaborate with international agencies and organizations to develop a pan-Arctic picture of change. To advance a U.S. AON, evolving these existing capabilities and advancing the utilization of next generation technologies is a multi-agency effort. Interagency collaboration can leverage sparse observing assets and propel the development of the next generation observing system. For example, in the past five years, technology development has surged. Gliders and floats that can measure horizontal and vertical properties of the ocean as well as conduct sea floor mapping have advanced to a level where they can be effectively deployed in the ice-covered Arctic basin. Autonomous surface vehicles and unmanned aircraft are now capable of long duration, autonomous missions, which can make millions of measurements of atmospheric and water properties, including pollutants, in previously inaccessible areas. When combined with fixed observational platforms, such as moorings, atmospheric monitoring facilities, and community-based observers, these systems can form the foundation of an integrated pan-Arctic observing network.

Performance Element 9.1.1: Coordinate U.S. agency and outside collaborators support for and participation in the international Sustaining Arctic Observing Networks (SAON) process.

Lead Agency: NOAA
Supporting Agencies: DHS (USCG), DOD (ONR), DOE, NASA, NSF

Performance Element 9.1.2: Work with the research community and other stakeholders to develop the concept of multi-agency research coordination networks to advance observational science and promote broad synthesis within thematic research communities. These networks would use a nested observing framework (satellite to ground observations) and include innovative and autonomous observing technologies suited to high latitude operations and community based observing.

Lead Agencies: NOAA, NSF
Supporting Agencies: DOD (ONR), DOE, NASA

Research Objective 9.2. Advance understanding of the Arctic System by using global and regional models with detailed Arctic processes to understand feedbacks and interactions within the components of the Arctic system and with the climate system as a whole.

Rationale: The Arctic environment is a complex system with many interacting components. The interdependencies in these components lead to positive and negative feedbacks. Variations in any one component will drive changes in the others, in ways that are not always obvious or well-understood. These variations include feedbacks between the Arctic and global system through cryosphere change and also feedbacks between cryospheric change and the local physical and biogeochemical responses that result in rapid changes within the Arctic region itself. For instance, amplified warming in the Arctic can influence mid-latitude weather patterns, but the underlying mechanisms of this relationship are not yet clear. The application of comprehensive, integrated global and regional earth system models will be needed to understand the interdependencies of the Arctic System and its relationship with the global earth system as a whole. Investments by DOE, NOAA, NASA, ONR and NSF in global and regional models, as well as efforts by interagency working groups such as the Climate Variability and Predictability (CLIVAR) Working Groups and U.S. Global Change Research activities can be leveraged as appropriate.

Performance Element 9.2.1: Support and coordinate research to advance understanding of the connections between the Arctic and mid-latitude weather patterns and vice-versa.

Lead Agencies: DOE, NOAA, NSF
Supporting Agencies: DOD (ONR), NASA

Performance Element 9.2.2: Support and coordinate research to enhance the understanding of connections between Arctic and global ocean circulation.

Lead Agencies: DOE, NOAA, NSF
Supporting Agencies: DOD (ONR), NASA

Performance Element 9.2.3: Enhance understanding of processes and their interactions and feedbacks within the Arctic System itself, including the complex relationships between the ocean, sea ice, land, and atmosphere; impacts of snow on ice; interactions between Arctic clouds and aerosols; effects of thermal forcing of sea ice; changes in ocean stratification; stratosphere-troposphere interactions; and radiative exchanges of energy throughout the system.

Lead Agencies: DOD (ONR), DOE, NOAA, NSF
Supporting Agency: NASA

Performance Element 9.2.4: Conduct a survey and identify investigator-driven modeling projects designed to understand important local and global Arctic System feedbacks.

Lead Agency: NSF
Supporting Agencies: DOD (ONR), DOE, NOAA, NASA

Research Objective 9.3. Enhance climate prediction capabilities for the Arctic System from sub-seasonal to decadal timescales and climate projection capabilities up to centennial timescales by focusing on improving earth system models and their interactions, and assessing the strengths and weaknesses of the various coupled regional Arctic and earth system models by conducting intercomparison and model evaluations.

Rationale: Regional and global earth system models are mathematical representations of scientific understanding of the interrelated feedbacks and processes in the earth. As new process models are developed based on understanding from new observations, they need to be incorporated into earth system models for a holistic representation of the feedbacks within the earth system. These models need to be evaluated against observations and compared against each other, to verify their veracity across a wide range of spatial and temporal scales. Climate modeling centers funded by different U.S. and international agencies are working on increasing the resolution and complexity of regional and global earth System models. Enhancements relevant to the Arctic include variable resolution models with higher resolution focused mainly on the Arctic, improved representation of ice-sheets, more realistic aerosol-cloud interactions, complex biogeochemical processes related to permafrost evolution and degradation, better ocean-ice and ice-snow process, to name a few. As part of the next phase of the Coupled Model Intercomparison Project (CMIP6), many of these models will be evaluated against observations and compared with each other. In addition, many agencies are supporting and developing capabilities for assimilation of observations and for prediction. Assimilation and reanalyses activities merge observations and earth system models and these can be used in validating and increasing scientific understanding of how well climate models perform, characterizing uncertainty in these models, while also guiding the next set of Arctic observations.

Performance Element 9.3.1: Support the configuration and the initial development of a global variable resolution model with very high resolution in the Arctic that will allow high-resolution interactions within the Arctic System and interactions between the Arctic and mid-latitudes.

Lead Agency: DOE
Supporting Agency: NSF

Performance Element 9.3.2: Support model development activities in global earth system models focusing on increased resolution, better coupling techniques, and inclusion of new process models in the Arctic for improved predictions, projections, and better representation of extreme events. In addition to developing models for CMIP6, this will include routine global ocean data assimilation capabilities linked to Global Ocean Observing System observations.

Lead Agencies: NOAA, NASA, NSF
Supporting Agency: DOE

Performance Element 9.3.3: Foster interactions between the Arctic Testbed and Environmental Modeling Center's weather modeling efforts to facilitate the improvement of model guidance at higher latitudes.

Lead Agency: NOAA
Supporting Agency: DOD (ONR)

Performance Element 9.3.4: Support model development of Regional Arctic System Models focusing on improved resolution, better coupling, inclusion of new process models, and better assimilation techniques for improved seasonal predictions.

Lead Agency: DOD (ONR)
Supporting Agencies: DOE, NSF

Performance Element 9.3.5: Support Systematic Improvements to Reanalyses of the Arctic (SIRTA) to address the need for improved models of Arctic weather, sea ice, glaciers, ecosystems, and other components of the Arctic System.

Lead Agencies: NOAA, NASA
Supporting Agencies: DOD (ONR), DOE, NSF

Performance Element 9.3.6: Coordinate and support the ISMIP6 efforts in the U.S. by integrating ice-sheet models into coupled climate and earth system models to both: (1) improve sea level projections due to changes in the cryosphere; and (2) enhance scientific understanding of the cryosphere in a changing climate.

Lead Agency: NASA
Supporting Agencies: DOE, NOAA, NSF

Research Objective 9.4. Enhance availability, discoverability, understanding, and interoperability of Arctic data and tools across Federal data centers.

Rationale: Many IARPC agencies invest in data stewardship and sponsor cyberinfrastructure projects toward improved tools and tool kits for data discovery, access, visualization, fusion, collaboration, and more. These centers, projects, and tools are a cornerstone of research advancement and decision support, yet there is significant progress needed to identify and link key assets, particularly across disciplinary boundaries, starting at project inception. IARPC Collaborations can serve as an on-going forum for encouraging data sharing and accessibility regionally, nationally and through serving as a hub for international coordination. International efforts are underway to advance models that describe existing capabilities and how they relate to one another, for example the "Mapping the Arctic Data Ecosystem" project coordinated by the International Arctic Science Committee-SAON (IASC-SAON) Arctic Data Committee in collaboration with EU—PolarNet, Group on Earth Observations (GEO), Global Earth Observation System of Systems (GEOSS), Pan-Arctic Options Project, Fram Centre (Norway), and others. In addition to tools for mapping capabilities, agencies would benefit from a shared vision for how data centers and tools could move toward greater interoperability. Such interoperability will enhance decision support and situational awareness efforts such as the Climate Resilience Toolkit (CRT), the Arctic Environmental Response Management Application (ERMA), the Arctic Collaborative Environment (ACE), and the ADAC's Arctic Information Fusion Capability. These activities are inherently tied to and benefit from the activities coordinated under Research Objective 9.5.

Performance Element 9.4.1: Advance system models of U.S. observing inventories and data centers to further understanding of these capacities so that informed, optimal, strategic decisions and design, and spending plans can be made.

Lead Agency: NOAA
Supporting Agencies: NASA, NSF

Performance Element 9.4.2: Promote a nationally and internationally interoperable Arctic data sharing system that will facilitate data discovery, access, usage in many contexts, and long-term preservation, building off the efforts of NSF's Arctic Data Center, the AOOS Regional Data Assembly Center and the Alaska Data Integration Working Group (ADIWG).

Lead Agencies: DOI (BLM, BOEM), NSF
Supporting Agencies: DOE, DOI (USGS), NOAA, NASA

Performance Element 9.4.3: Enhance the timely availability, diversity of content, and inclusion of international contributions to the Arctic data sets and resilience tools within the Arctic Theme for the Climate Data Initiative (CDI) and CRT.

Lead Agencies: DOI, NOAA, NASA, NSF

Performance Element 9.4.4: Advance agile situational awareness and decision support for Arctic operators through efforts like ADAC's Arctic Information Fusion Capability[28], ERMA, and NASA ACE project.

Lead Agency: DHS
Supporting Agencies: DOE, NOAA, NASA

Performance Element 9.4.5: Update baseline mapping and charting across the Arctic, including additional charting in Arctic waters, updates to baseline topographic mapping and supporting data, and updating high resolution imagery-derived elevation data repeated coverage. Multiagency partners include Alaska Mapping Executive Committee, Alaska Geospatial Council, and Arctic-related LCCs.

Lead Agencies: DOI (USGS), NOAA, NSF
Supporting Agencies: DOD (NGA), DOI (BLM, FWS, NPS)

Research Objective 9.5. Advance research, tools, and strategies to improve the accessibility and relevance of Arctic science for decision support.

Rationale: It is well accepted that effective knowledge exchange for decision support occurs through sustained activities between researchers and decision makers where key issues and indicators can be jointly identified and analyzed, ideally from the time of project inception. This collaboration supports a co-production of new knowledge that is clearly relevant and easily accessible for stakeholders. The efforts described in this Research Objective support and influence practices within the other Research Objectives of Environmental Intelligence. Many Federally funded organizations listed in the introduction include sponsorships to convene regional forums and conduct research to advance dialog, identify decision needs, and support relevant knowledge development. These activities draw together research communities, operators and other stakeholders to support decision-making around issue-specific foci (e.g., ocean acidification, integrated water level observations, emergency response) or geographic areas (e.g., western Alaska, North Slope). The interagency platform can serve to share best practices and enhance coordination of existing capabilities.

[28] ADAC is a university recipient of DHS funding under a cooperative agreement. ADAC conducts research relevant to enhancing maritime domain awareness for the Arctic environment based on DHS mission-relevancy.

Performance Element 9.5.1: Advance coordination among Federally-funded research programs that provide decision support to Arctic stakeholders.

Lead Agency: NOAA
Supporting Agencies: DHS, DOI (BLM, FWS)

Performance Element 9.5.2: Advance policy-relevant science communication through efforts like the annual *Arctic Report Card,*[29] the Arctic Research Consortium of the United States (ARCUS), and SEARCH.

Lead Agencies: NOAA, NSF
Supporting Agencies: DOD (ONR), DOI (BOEM), NASA

[29] The Arctic Report Card has been issued annually since 2006. It is a timely and peer-reviewed source for clear, reliable and concise environmental information on the current state of different components of the Arctic environmental system relative to historical records.www.arctic.noaa.gov/reportcard

Appendix 1

IARPC Agencies

National Science Foundation (Chair)

Department of Agriculture

Department of Commerce

Department of Defense

Department of Energy

Department of Health and Human Services

Department of Homeland Security

Department of the Interior

Department of State

Department of Transportation

Environmental Protection Agency

Marine Mammal Commission

National Aeronautics and Space Administration

Office of Management and Budget

Office of Science and Technology Policy

Smithsonian Institution

Appendix 2

Implementing the IARPC Arctic Research Plan FY2017-2021 with IARPC Collaborations

IARPC Collaborations is the primary structure for implementing the Plan. Membership is open to anyone who can contribute to efforts to implement the Plan, and thus it serves as a mechanism for bringing together Federal government program managers, the research community, and other stakeholders to accelerate the pace of Arctic research.

To implement the Plan, IARPC Collaborations will be organized into nine thematic Collaboration Teams, each corresponding to one of the nine Research Goals in the Plan. Each team will be co-chaired by a Federal program manager and a co-chair from a different Federal agency or a non-federal partner. Collaboration teams will meet virtually on a regular basis to discuss updates to Performance Elements and share information relevant to accomplishing research objectives.

The IARPC Collaborations website at **www.iarpccollaborations.org** is the primary tool that IARPC Collaborations members use to communicate and collaborate between team meetings. It was designed to support implementation of the IARPC Arctic Research Plan FY2013-2017. The website serves dual purposes as both a content driven dialogue system and a project management and tracking system.

(1) *Content driven dialogue system*. In order to share information, generate ideas, and form opportunities for collaboration, IARPC Collaborations members log into the member space of the website and post updates, documents, and events related to their or their organizations' research or Arctic-related activities. These posts are permanently archived on and available to any member of IARPC Collaborations through the website. Open dialogue is encouraged through the comment section available on every post and "@tagging" system which allows interaction with any specific website member.

(2) *A project management and tracking system*. Through event and document posting, the website serves as the platform for organizing collaboration team meetings and delivering meeting information to team members. The performance element database section of the website keeps a record of specific actions taken on Performance Elements as well as information on people, agencies, collaboration teams, and deadlines involved. Team leaders and website administrators can enter actions on Performance Elements directly into the database, while any member can submit an action to a performance element by commenting or posting. The database can be exported into a report format for annual and biennial reporting.

The IARPC Collaborations, collaboration teams, and the website are open to anyone who can contribute to IARPC's efforts to implement the Plan. Request an account by entering your contact information and a brief explanation of your background and interest in Arctic research at http://www.iarpccollaborations.org/request-account.html

Each fall team leaders will produce summary accomplishment reports for IARPC Principals and in support of the National Strategy for the Arctic Region. Additionally, the secretariat will produce a biannual report summarizing accomplishments by policy driver in order to better understand how the various efforts in the plan relate to each other in the context of the policy drivers.

Collaboration Team leaders will develop annual implementation plans which focus on Research Objectives and Performance Elements to be accomplished in the upcoming year. Their plans will include meeting schedules with specific references to how the meetings support plan implementation.

Collaboration Team leads will coordinate their scheduling in order to promote coordination between teams pursuing related activities. For example, several teams may coordinate their meetings and activities around the cross-cutting theme of food security or the carbon budget.

The IARPC secretariat will host annual meetings of team leaders to support inter-team coordination. At this time, team leaders will explore overlapping Research Objectives and Performance Elements and pursue a joint course of action around related activities.

Regular Federal-only meetings will be arranged for agency representatives to explore collaborations to address cross-cutting issues for which multiple agencies are responsible.

The IARPC Staff Group and Principals will continually examine how well IARPC is addressing research Goals and Objectives in support of the policy drivers and how well the policy drivers are providing a framework for integration across the plan.

Appendix 3

How USARC Goals Inform the IARPC Arctic Research Plan FY2017-2021

The Arctic Research Policy Act (ARPA) establishes the relationship between IARPC and USARC and calls for IARPC to build a 5-Year Arctic Research Plan (hereafter the Plan) “in consultation with the Commission, the Governor of the State of Alaska, the residents of the Arctic, the private sector, and public interest groups.” In accordance with ARPA, the biennial USARC Goals and Objectives Report (hereafter the Report) provides key input in developing this Plan. This appendix to the 2017-2021 Plan summarizes the IARPC response to the USARC Goals Report 2015-2016, and provides an explanation for occasional divergence from it. While the structure and purpose of the two documents are distinct, connections to the Report are found at all levels in the Plan. It is important to note that, while the Report looks broadly at how Federally-sponsored research could address emerging and persistent needs, the IARPC Plan is only focused on topics requiring interagency collaboration. Specifically, this means that Arctic research topics addressed by individual federal agencies are not included in the Plan. The six goals in the USARC Report are:

(1) Arctic Environmental Change;
(2) Arctic Human Health;
(3) Arctic Natural Resources;
(4) The Arctic “Built Environment”;
(5) Arctic Cultures and Community Resilience;
(6) International Scientific Cooperation.

The structure of the IARPC Plan is tiered, and begins with Policy Drivers and Implementation Strategies. The Policy Drivers of *Well-being*, *Stewardship*, *Security*, and *Arctic-Global Systems* are high-level and capture the scope of all six of USARC’s goals. The Plan’s Implementation Strategies address *how* IARPC will coordinate research, and again, the USARC goals are reflected in these principles. The principles include integration of basic and applied research, and that Arctic research should be conducted in collaboration with indigenous and international partners.

The IAPRC Plan has nine Research Goals. Each reflect a topic that the USARC Report considers important. In some cases, the Report identifies a research objective that is not reflected in the IARPC Plan. There are two fundamental explanations for this. The first is when other federal interagency work is already addressing an issue identified by USARC; IARPC sought a non-duplicative and exclusive Plan. For example, the Report highlights the important issue of ocean acidification in the Arctic, which is covered by the interagency Subcommittee on Ocean Science and Technology (SOST). And the Report stresses the importance of research into oil pollution prevention and response in Arctic waters, which is addressed by the Interagency Coordinating Committee on Oil Pollution Research (ICCOPR). The second occurs when there are limited Federal activities addressing a topic recommended by the Commission, or it is the remit of a single agency. For example, the Report identifies topics, like socio-economic research focused on the North, yet there are limited Federally-funded efforts to coordinate across agencies. In other cases, like renewable energy, there is significant Federal work, but interagency efforts have only recently been initiated and will take more time to develop concrete objectives.

Here are several examples where the Plan clearly reflects USARC recommendations:

The Plan reflects the Report’s emphasis on efforts to enhance research on Arctic environmental change (USARC Goal 1) in multiple ways, and examples include: (1) a focus on ecosystem interactions among marine trophic levels and their impacts on human communities; (2) interagency efforts to understand the warming-induced degradation of permafrost and other components of the cryosphere such as glaciers and sea ice; and (3) research to understand how change in fire activity is impacting rural and urban communities and atmospheric emissions.

Additionally, USARC calls for greater support of scientific monitoring and improved modeling of the Arctic System along with improved data sharing and integration (USARC Goal 1). The Plan responds vigorously through its Research Goal on Environmental Intelligence, which emphasizes systems research and the need to integrate observations, data sharing and modeling across all areas of foundational science in support of improving scientific understanding of Arctic environmental change.

The Plan’s responsiveness to the USARC’s emphasis on human health (USARC Goal 2) can be seen in IARPC’s Research Goal on human health and well-being through its support for (1) research seeking to explore the interconnections between human health and the natural environment; (2) community monitoring of environmental impacts associated with climate change on health, and research to increase understanding and surveillance of diseases, especially climate sensitive diseases; (3) efforts surrounding health-care education, water quality and sanitation innovations, improving indoor air-quality, and by supporting residents to become involved in health care processes; (4) research on violence against Alaskan Native women and children; and (5) efforts to improve effectiveness of responses, support health care delivery across the Arctic through methods like telemedicine.

Some emerging work in the Plan relates to Report recommendations towards the “built environment” (USARC Goal 4) and community resilience (USARC Goal 5). New efforts under the Permafrost and Coastal Research Goals consider the impacts of permafrost degradation and coastal erosion on infrastructure. Issues related to community resilience are woven directly into the Health and Well-being Research Goal, for example research on the resilience of Alaskan Youth, and are present in community-based research approaches organized under the Coastal Research Goal.

Although the Plan spans a five-year period, Performance Elements are designed to be completed within two years and new Performance Elements will be designed to take their place. With this “living document” structure, IARPC hopes, through collaboration with partners like USARC, to grow the Plan’s focus on socio-economic research and renewable energy in the next two years. IARPC enjoys a beneficial partnership with USARC and looks forward to their next Report.

References

Abbott, B. W., J. R. Larouche, J. B. Jones Jr., W. B. Bowden, and A. W. Balser. 2014. “Elevated Dissolved Organic Carbon Biodegradability from Thawing and Collapsing Permafrost.” *Journal of Geophysical Research: Biogeosciences*, 119. doi:10.1002/2014JG002678.

ACIA Secretariat and Cooperative Institute for Arctic Research. 2005. “Impacts of a Warming Arctic: Arctic Climate Impact Assessment.” New York: University of Alaska Fairbanks.

Alaska Arctic Policy Commission. 2015. “Final Report of Alaska Arctic Policy Commission.” Alaska Arctic Policy Commission. www.akarctic.com/wp-content/uploads/2015/01/AAPC_final_report_lowres.pdf.

AMAP. 2015. “AMAP Assessment 2015: Black Carbon and Ozone as Arctic Climate Forcers.” *Arctic Monitoring and Assessment Programme (AMAP).* Oslo, Norway. http://www.amap.no.

Arnold, S. R., K. S. Law, C. A. Brock, J. L. Thomas, S. M. Starkweather, K. von Salzen, A. Stohl, S. Sharma, M. T. Lund, M. G. Flanner, T. Petäjä, H. Tanimoto, J. Gamble, J. E. Dibb, M. Melamed, N. Johnson, M. Fidel, V. P. Tynkkynen, and A. Baklanov. 2016. “Arctic Air Pollution: Challenges and Opportunities for the Next Decade.” *Elementa Science Anthology* 4. doi: 10.12952/journal.elementa.000104.

Balser, A. W., and J. B. Jones. 2015. “Drivers and Estimates of Terrain Suitability for Active Layer Detachment Slides and Retrogressive Thaw Slumps in the Brooks Range and Foothills of Northwest Alaska, USA.” *Journal of Geophysical Research: Earth Surface,* in review.

Balser, A. W., J. B. Jones, and M. T. Jorgenson. 2015. Relationship of Permafrost Cryofacies, Surface and Subsurface Terrain Conditions in the Brooks Range and Foothills of Northern Alaska. University of Alaska Fairbanks. Fairbanks, AK.

Balser, A. W., J. B. Jones, and R. Gens. 2014. “Timing of Retrogressive Thaw Slump Initiation in the Noatak Basin, Northwest Alaska, USA.” *Journal of Geophysical Research: Earth Surface* 119 (May): 1106-1120. doi:10.1002/2013JF002889.

Bernhardt, E. L., T. N. Hollingsworth, and F. S. Chapin, III. 2011. “Fire Severity Mediates Climate-driven Shifts in Understorey Community Composition of Black Spruce Stands of Interior Alaska.” *Journal of Vegetation Science* 22: 32–44. doi:10.1111/j.1654-1103.2010.01231.x.

Bhatt, U. S., D. A. Walker, M. K. Raynolds, P. A. Bieniek, H. E. Epstein, J. C. Comiso, J. E. Pinzon, C. J. Tucker, and I. V. Polyakov. 2013. “Recent Declines in Warming and Vegetation Greening Trends over Pan-Arctic Tundra.” *Remote Sensing* 5: 4229-4254. doi:10.3390/rs5094229.

Bluhm, B. A., and R. Gradinger. 2008. “Regional Variability in Food Availability for Arctic Marine Mammals.” *Ecological Applications* 18, no. 2: 77-96. doi: 10.1890/06-0562.1

Bourassa, M. A., S. T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C. A. Clayson, M. F. Cronin, W. M. Drennan, C. W. Fairall, R. N. Hoffman, G. Magnusdottir, R. T. Pinker, I. A. Renfrew, M. Serreze, K. Speer, L. D. Talley, and G. A. Wick. 2013. “High-Latitude Ocean and Sea Ice Surface Fluxes: Challenges for Climate Research.” *Bulletin of the American Meteorological Society* 94: 402-423. doi: 10.1175/bams-d-11-00244.1.

Bowden, W., J. R. Larouche, A. R. Pearce, B. T. Crosby, K. Krieger, M. B. Flinn, J. Kampman, M. N. Gooseff, S. E. Godsey, J. B. Jones, B. W. Abbott, M. T. Jorgenson, G. W. Kling, M. Mack, E. A. G. Schuur, A. F. Baron, and E. B. Rastetter. 2012. “An Integrated Assessment of the Influences of Upland Thermal-Erosional Features on Landscape Structure and Function in the Foothills of the Brooks Range Alaska.” *International Contributions* 1. Salekhard, Russia: The Northern Publisher.

Brown, J., O. J. Ferrians, J. A. Heginbottom, and E. S. Melnikov. 1998, revised February 2001. “Circum-Arctic Map of Permafrost and Ground Ice Conditions.” National Snow and Ice Data Center. Boulder, Colorado.

Bunn, A. G., and S. J. Goetz. 2006. "Trends in Satellite-observed Circumpolar Photosynthetic Activity from 1982 to 2003: the Influence of Seasonality, Cover Type, and Vegetation Density." *Earth Interact* 10: 1–19. doi:10.1175/EI190.1.

Cable, W. L., V. E. Romanovsky, and M. T. Jorgenson. 2016. "Scaling-up Permafrost Thermal Measurements in Western Alaska using an Ecotype Approach" *The Cryosphere Discussions*. doi:10.5194/tc-2016-30.

Chapin, F. S. III, A. D. McGuire, R. W. Ruess, T. N. Hollingsworth, M. C. Mack, J. F. Johnstone, E. S. Kasischke, E. S. Euskirchen, J. B. Jones, M. T. Jorgenson, K. Kielland, G. P. Kofinas, J. Yarie, and D. L. Taylor. 2010. "Resilience to Climate Change in Alaska's Boreal Forest." *Canadian Journal of Forest Research* 40: 1360-1370. doi:10.1139/X10-074.

Clarke, J., K. Stafford, S. E. Moore, B. Rone, L. Aerts, and J. Crance. 2013. "Subarctic Cetaceans in the Southern Chukchi Sea: Evidence of Recovery or Response to a Changing Ecosystem." *Oceanography* 26 (April): 136-149. doi:10.5670/oceanog.2013.81.

Cohen, J., J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones. 2014. "Recent Arctic Amplification and Extreme Mid-latitude Weather." *Nature Geoscience* 7: 627-637. doi:10.1038/NGEO2234.

Coyle, K. O., B. Konar, A. Blanchard, R. C. Highsmith, J. Carroll, M. Carroll, S. G. Denisenko, and B. I. Sirenko. 2007. "Potential Effects of Temperature on the Benthic Infaunal Community on the Southeastern Bering Sea Shelf: Possible Impacts of Climate Change." *Deep Sea Research Part II* 54: 2885–2905. doi:10.1016/j.dsr2.2007.08.025.

de Boer, G., W. Chapman, J. Kay, B. Medeiros, M. D. Shupe, S. Vavrus, and J. E. Walsh. 2014. "A Characterization of the Arctic Atmosphere in CCSM4." *Journal of Climate* 25: 2676-2695. doi:10.1175/JCLI-D-11-00228.1.

de Boer, G., T. Hashino, G. J. Tripoli, and E. W. Eloranta 2013. "A Numerical Study of Aerosol Influence on Ice Nucleation via the Immersion Mode in Mixed-Phase Stratiform Clouds." *Atmospheric Chemistry and Physics* 13: 1733-1749. doi:10.5194/acp-13-1733-2013.

Department of Defense. 2013. "Arctic Strategy." Washington, DC: Department of Defense. www.defense.gov/Portals/1/Documents/pubs/2013_Arctic_Strategy.pdf.

Eicken, H., A. L. Lovecraft, and M. L. Druckenmiller. 2009. "Sea-ice System Services: A Framework to Help Identify and Meet Information Needs Relevant for Arctic Observing Networks." *Arctic* 62: 119-138. www.seaice.alaska.edu/gi/publications/druckenmiller/Eicken2009Arctic.pdf.

Einarsson, N., J. N. Larsen, A. Nilsson, and O. R. Young. 2004. "Arctic Human Development Report." Akureyri: Stefansson Arctic Institute. www.oaarchive.arctic-council.org/handle/11374/51.

Epstein, H. E., M. K. Raynolds, D. A. Walker, U. S. Bhatt, C. J. Tucker, and J. E. Pinzon. 2010. "Dynamics of Aboveground Phytomass of the Circumpolar Arctic Tundra During the Past Three Decades." *Environmental Research Letters* 7, no. 1: Article no. 015506. doi:10.1088/1748-9326/7/1/015506.

Fay, F. H., and B. P. Kelly. 1980. "Mass Natural Mortality of Walruses (Odobenus rosmarus) at St. Lawrence Island, Bering Sea, Autumn 1978." *Arctic* 33: 226-245.

Fetterer, F., K. Knowles, W. Meier, and M. Savoie. 2002. "Sea Ice Index." *National Snow and Ice Data Center*. Boulder, Colorado.

Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch. 2007. "Present Day Climate Forcing and Response from Black Carbon in Snow." *Journal of Geophysical Research* 112 D11202. doi:10.1029/2006JD008003.

Francis, J., S. J. Vavrus, and Q. Tang. 2014. "Rapid Arctic Warming and Mid-Latitude Weather Patterns: Are they Connected? State of the Climate in 2013." *Bulletin of the American Meteorological Society* 96: 136-137. doi:10.1175/2014BAMSStateoftheClimate.1.

Frey, K., J. C. Comiso, L. W. Cooper, R. R. Gradinger, J. M. Grebmeier, and J. E. Tremblay. 2015. "Ocean Primary Productivity." *Arctic Report Card: Update for 2015, Tracking Recent Environmental Changes*. www.arctic.noaa.gov/reportcard/sea_ice.html.

Gardner, A. S., G. Moholdt, J. G. Cogley, B. Wouters, A. A. Arendt, J. Wahr, E. Berthier, R. Hock, W. T. Pfeffer, G. Kaser, S. R. M. Ligtenberg, T. Bolch, M. J. Sharp, J. O. Hagen, M. R. van den Broeke, and F. Paule. 2013. "A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009." *Science 340* 6134: 852-857. doi:10.1126/science.1234532.

Garrett, T. J., and C. Zhao. 2006. "Increased Arctic Cloud Longwave Emissivity Associated with Pollution from Mid-latitudes." *Nature* 440. doi:10.1038/nature04636.

Gibbs, A. E., and B. M. Richmond. 2015. "National Assessment of Shoreline Change—Historical Shoreline Change along the North Coast of Alaska, U.S.–Canadian Border to Icy Cape." *U.S. Geological Survey Open-File Report 2015–1048* 96. doi:10.3133/ofr20151048.

Gooseff, M., A. Balser, W. Bowden, and J. Jones. 2009. "Effects of Hillslope Thermokarst in Northern Alaska." *Eos, Transactions of the American Geophysical Union* 90 (April): 29-31. www.mdpi.com/2072-4292/5/6/2813/htm.

Grebmeier, J. M. 2012. "Shifting Patterns of Life in the Pacific Arctic and Sub-Arctic Seas." *Annual Review of Marine Science* 4: 63–78. doi:10.1146/annurev-marine-120710-100926.

Grebmeier, J. M., and W. Maslowski. 2014. *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment.* Dordrecht: Springer Netherlands. doi:10.1007/978-94-017-8863-2_1.

Grebmeier, J. M., J. E. Overland, S. E. Moore, E. V. Farley, E. C. Carmack, L. W. Cooper, K. E. Frey, J. H. Helle, F. A. McLaughlin, and S. L. McNutt. 2006. "A Major Ecosystem Shift in the Northern Bering Sea." *Science* 311: 1461–1464. doi:10.1126/science.1121365.

Grosse, G., J. Harden, M. Turetsky, A. D. McGuire, P. Camill, C. Tarnocai, S. Frolking, E. A. G. Schuur, T. Jorgenson, S. Marchenko, V. Romanovsky, K. P. Wickland, N. French, M. Waldrop, L. Bourgeau-Chavez, and R. G. Striegl. 2011. "Vulnerability of High-latitude Soil Organic Carbon in North America to Disturbance." *Journal of Geophysical Research: Biogeosciences* 116, G00K06. doi:10.1029/2010JG001507.

Harwood, L. A., T. G. Smith, J. C. George, S. J. Sandstrom, W. Walkusz, and G. J. Divoky. 2015. "Change in the Beaufort Sea Ecosystem: Diverging Trends in Body Condition and/or Production in Five Marine Vertebrate Species." *Progress in Oceanography* 136: 263-273. doi:10.1016/j.pocean.2015.05.003.

Hay, C. C., E. Morrow, R. E. Kopp, and J. X. Mitrovica, 2015. "Probabilistic Reanalysis of Twentieth-century Sea-level Rise." *Nature* 517: 481-484, doi:10.1038/nature14093.

Higuera, P. E., L.B. Brubaker, P.M. Anderson, T.A. Brown, A.T. Kennedy, F.S. Hu, and J. Chave. 2008. "Frequent Fires in Ancient Shrub Tundra: Implications of Paleorecords for Arctic Environmental Change." *PLoS ONE* 3 e0001744. doi:10.1371/journal.pone.0001744.

Hill, G. B., and G. H. R. Henry. 2011. "Responses of High Arctic Wet Sedge Tundra to Climate Warming Since 1980." *Global Change Biology* 17: 276–87. doi:10.1111/j.1365-2486.2010.02244.x.

Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin, M. B. Dyurgerov, C. L. Fastie, B. Griffith, R. D. Hollister, A. Hope, H. P. Huntington, A. M. Jensen, G. J. Jia, T. Jorgenson, D. L. Kane, D. R. Klein, G. Kofinas, A. H. Lynch, A. H. Lloyd, A. D. McGuire, F. E. Nelson, W. C. Oechel, T. E. Osterkamp, C. H. Racine, V. E. Romanovsky, R. S. Stone, D. A. Stow, M. Sturm, C. E. Tweedie, G. L. Vourlitis, M. D. Walker, D. A. Walker, P. J. Webber, J. M. Welker, K. S. Winker, and K. Yoshikawa. 2005. "Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions." *Climatic Change* 72, no. 3: 251-298. doi:10.1007/s10584-005-5352-2.

Hinzman, L. D., W. R. Bolton, K. Petrone, J. Jones, K. Yoshikawa, and J. P. McNamara. "Permafrost Degradation and Effects on Watershed Chemistry and Hydrology" (Paper presented at American Geophysical Union Fall Meeting, San Francisco, California, 2006).

Huntington, H. P. 2009. “A Preliminary Assessment of Threats to Arctic Marine Mammals and Their Conservation in the Coming Decades.” *Marine Policy* 33, no. 1: 77-82. doi:10.1016/j.marpol.2008.04.003.

Iacozza, J., and S. H. Ferguson. 2014. “Spatio-temporal Variability of Snow Over Sea Ice in Western Hudson Bay, with Reference to Ringed Seal Pup Survival.” *Polar Biology* 37: 817-832. doi:10.1007/s00300-014-1484-z

Intrieri, J. M., C. W. Fairall, M. D. Shupe, P. O. G. Persson, E. L. Andreas, P. S. Guest, and R. E. Moritz. 2002. "An Annual Cycle of Arctic Surface Cloud Forcing at SHEBA." *Journal of Geophysical Research* 107, no. C10: 8039. doi:10.1029/2000JC00439.

ICC. 2016. Inuit Arctic Policy. Alaska: Inuit Circumpolar Council. iccalaska.org/wp-icc/wp-content/uploads/2016/01/Inuit-Arctic-Policy-June02_FINAL.pdf.

ICC-Alaska. 2015. “Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective.” Technical Report. Anchorage, AK.

IPCC. 2014. “Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.” R. K. Pachauri and L. A. Meyer (eds.). IPCC, Geneva, Switzerland. https://www.ipcc.ch/report/ar5/syr/

Jay, C., A. Fischbach, and A. Kochnev. 2012. "Walrus Areas of Use in the Chukchi Sea During Sparse Sea Ice Cover." *Inter-Research Marine Ecology Progress Series* 468: 1–13. doi:10.3354/meps10057.

Johnstone, J. F., F. S. Chapin, III, T. N. Hollingsworth, M. C. Mack, V. Romanovsky, and M. Turetsky. 2010. “Fire, Climate Change, and Forest Resilience in Interior Alaska.” *Canadian Journal of Forest Research* 40: 1302-1312. doi:10.1139/X10-061.

Joly, K., C. Nellemann, and I. Vistnes. 2006. “A Reevaluation of Caribou Distribution Near an Oilfield Road on Alaska' s North Slope.” *Wildlife Society Bulletin* 34: 866–869. doi:10.2193/0091-7648(2006)34[870:RTJEAA]2.0.CO;2.

Jones, B. M., G. Grosse, C. D. Arp, E. Miller, L. Liu, D. J. Hayes, and C. F. Larsen. 2015. “Recent Arctic Tundra Fire Initiates Widespread Thermokarst Development.” *Scientific Reports* 5.doi:10.1038/srep15865.

Jones, B. M., A. L. Breen, B. V. Gaglioti, D. H. Mann, A. V. Rocha, G. Grosse, C. D. Arp, M. L. Kunz, and D. A. Walker. 2013. “Identification of Unrecognized Tundra Fire Events on the North Slope of Alaska.” *Journal of Geophysical Research* 118. doi:10.1002/jgrg.20113.

Jorgenson, M. T., J. Harden, M. Kanevskiy, J. O’Donnell, K. Wickland,, S. Ewing, K. Manies, Q. Zhuang, Y. Shur, R. Striegl, and J. Koch. 2013. “Reorganization of Vegetation, Hydrology and Soil Carbon after Permafrost Degradation across Heterogeneous Boreal Landscapes.” *Environmental Research Letters* 8, no. 3: 035017. doi:10.1088/1748-9326/8/3/035017.

Jorgenson, M. T., M. Kanevskiy, Y. Shur, J. Grunblatt, C. Ping, and G. Michaelson. 2014. "Permafrost Database Development, Characterization, and Mapping for Northern Alaska." *Report U.S. Fish & Wildlife Service*, Arctic Landscape Conservation Cooperative.

Jorgenson, M. T., C. H. Racine, J. C. Walters, and T. E. Osterkamp. 2001. “Permafrost Degradation and Ecological Changes Associated with a Warming Climate in Central Alaska.” *Climate Change* 48, no. 4: 551–579. doi:10.1023/A:1005667424292.

Jorgenson, M. T., V. Romanovsky, J. Harden, Y. Shur, J. O’Donnell, E. A. G. Schuur, M. Kanevskiy, and S. Marchenko. 2010. “Resilience and Vulnerability of Permafrost to Climate Change.” *Canadian Journal of Forest Research* 40, no. 7: 1219–1236. doi:10.1139/X10-060.

Jorgenson, M. T., Y. Shur, and E. R. Pullman. 2006. “Abrupt Increase in Permafrost Degradation in Arctic Alaska.” *Geophyical Research Letters* 33, no. 2. doi:10.1029/2005GL024960.

Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones. 2008. “Permafrost Characteristics of Alaska: Ninth International Conference on Permafrost.” University of Alaska Fairbanks. 183–184. Fairbanks, Alaska.

Kasischke, E. S., D. L. Verbyla, T. S. Rupp, A. D. McGuire, K. A. Murphy, R. Jandt, J. L. Barnes, E. E. Hoy, P. A. Duffy, M. Calef, and M. R. Turetsky. 2010. “Alaska's Changing Fire Regime - Implications for the Vulnerability of its Boreal Forests.” *Canadian Journal of Forest Research* 40: 1313-1324. doi:10.1139/X10-098.

Kasischke, E. S., and E. E. Hoy. 2012. “Controls on Carbon Consumption during Alaskan Wildland Fires.” *Global Change Biology* 18: 685-699. doi:10.1111/j.1365-2486.2011.02573.x.

Kedra, M., C. Moritz, E. Choy, C. David, R. Degen, S. Duerksen, I. Ellingsen, B. Górska, J. Grebmeier, D. Kirievskaya, D. van Oevelen, K. Piwosz, A. Samuelsen, and J. Węsławski. 2015. “Status and Trends in the Structure of Arctic Benthic Food Webs.” *Polar Research* 34: 23755, doi:10.3402/polar.v34.23775.

Kelly, B. P., J. L. Bengtson, P. L. Boveng, M. F. Cameron, S. P. Dahle, J. K. Jansen, E. A. Logerwell, J. E. Overland, C. L. Sabine, G. T. Waring, and J. M. Wilder. 2010. “Status Review of the Ringed Seal (Phoca hispida).” U.S. Department of Commerce, *NOAA Technical Memorandum NMFS-AFSC-212*.

Kelly, R., M. L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F. Sheng Hua. 2013. “Recent Burning of Boreal Forests Exceeds Fire Regime Limits of the Past 10,000 Years.” *PNAS* 32: 13055–13060. doi:10.1073/pnas.1305069110.

Kim, Y. J.S. Kimball, K. Zhang, and K. C. McDonald. 2012. “Satellite Detection of Increasing Northern Hemisphere Non-frozen Seasons from 1979 to 2008: Implications for regional vegetation growth.” *Remote Sensing of Environment* 121, 472-487. doi:10.1016/j.rse.2012.02.014

Kofinas, G. P., F. S. Chapin III, S. Burn-Silver, J. I. Schmidt, N. L. Fresco, K. Kielland, S. Martin, A. Springsteen, and T. S. Rupp. 2010. “Resilience of Athabascan Subsistence Systems to Interior Alaska's Changing Climate.” *Canadian Journal of Forest Research* 40: 1347-1359. doi:10.1139/X10-108.

Kokelj, S. V., J. Tunnicliffe, D. Lacelle, T. C. Lantz, K. S. Chin, and R. Fraser. 2015. “Increased Precipitation Drives Mega Slump Development and Destabilization of Ice-rich Permafrost Terrain, Northwestern Canada.” *Global and Planetary Change* 129: 56–68. doi:10.1016/j.gloplacha.2015.02.008.

Koven, C. D., E. A. G. Schuur, C. Schadel, T. J. Bohn, E. J. Burke, G. Chen, X. Chen, P. Ciais, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, E. E. Jafarov, G. Krinner, P. Kuhry, D. M. Lawrence, A. H. MacDougall, S. S. Marchenko, A. D. McGuire, S. M. Natali, D. J. Nicolsky, D. Olefeldt, S. Peng, V. E. Romanovsky, K. M. Schaefer, J. Strauss, C. C. Treat, and M. Turetsky. 2015. “A Simplified, Data-constrained Approach to Estimate the Permafrost Carbon-climate Feedback.” *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 373. doi: 10.1098/rsta.2014.0423.

Kwok, R., and D. Rothrock. 2009. “Decline in Arctic Sea Ice Thickness From Submarine and ICESat Records: 1958–2008.” *Geophysical Research Letters* 36. doi:10.1029/2009GL039035.

Kwok, R., and N. Untersteiner. 2011. "The Thinning of Arctic Sea Ice." *Physics Today* 64: 36-41. doi:10.1063/1.3580491.

Kwok, R., G. Spreen, and S. Pang. 2013. “Arctic Sea Ice Circulation and Drift Speed: Decadal Trends and Ocean Currents.” *Journal of Geophysical Research* 118: 2408-2425. doi:10.1002/jgrc.20191.

Laidre, K. L., H. Stern, K. M. Kovacs, L. Lowry, S. E. Moore, E. V. Regehr, S. H. Ferguson, O. Wiig, P. Boveng, R. P. Angliss, E. W. Born, D. Litovka, L. Quakenbush, C. Lydersen, D. Vongraven, and F. Ugarte. 2015. "Arctic Marine Mammal Population Status, Sea Ice Habitat Loss, and Conservation Recommendations for the 21st Century." *Conservation Biology* 29, no. 3: 724-737. doi:10.1111/cobi.12474.

Lantz, T. C., and S. V. Kokelj. 2008. “Increasing rates of Retrogressive Thaw Slump Activity in the Mackenzie Delta Region, N.W.T., Canada.” *Geophysical Research Letters* 35, no. 6. doi:10.1029/2007GL032433.

Larsen, J. N., and G. Fondahl. 2014. “Arctic Human Development Report II: Regional Processes and Global Linkages.” Denmark: Rosendahls-Schultz Grafisk. doi.org/10.6027/TN2014-567.

Larsen, P. H., S. Goldsmith, O. Smith, M. L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor. 2008. "Estimating Future Costs for Alaska Public Infrastructure at Risk from Climate Change." *Global Environmental Change-Human and Policy Dimensions* 18, no. 3: 442-457. doi:10.1016/j.gloenvcha.2008.03.005.

Li, W. K. W., F. A. McLaughlin, C. Lovejo, and E. C. Carmack. 2009. "Smallest Algae Thrive as the Arctic Ocean Freshens." *Science* 326: 539. doi:10.1126/science.1179798.

Liljedahl, A. K., J. Boike, R. P. Daanen, A. N. Fedorov, G. V. Frost, G. Grosse, L.D. Hinzman, Y. Iijima, J. C. Jorgensen, N. Matveyeva, and M. Necsoiu. 2016. "Pan-Arctic Ice-wedge Degradation in Warming Permafrost and its Influence on Tundra Hydrology." *Nature Geoscience* 9: 312-318. doi:10.1038/NGEO2674.

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, and D. L. Verbyla. 2011. "Carbon Loss from an Unprecedented Arctic Tundra Wildfire." *Nature* 475, no. 7357: 489-492. doi:10.1098/rstb.2012.0490.

Marsh, R., D. Desbruyeres, J. L. Bamber, B. A. de Cuevas, A. C. Coward, and Y. Aksenov. 2010. "Short-term Impacts of Enhanced Greenland Freshwater Fluxes in an Eddy-permitting Ocean Model." *Ocean Science* 6: 749–760, doi:10.5194/os-6-749-2010.

Matsuno, K., A. Yamaguchi, T. Hirawake, and I. Imai. 2011. "Year-to-year Changes of the Mesozooplankton Community in the Chukchi Sea during Summers of 1991, 1992 and 2007, 2008." *Polar Biology* 34: 1349–1360. doi:10.1007/s00300-011-0988-z.

Mecklenburg, C. W., D. L. Stein, B. A. Sheiko, N. V. Chernova, T. A. Mecklenburg, and B. A. Holladay. 2007. "Russian-American Long-Term Census of the Arctic: Benthic Fishes Trawled in the Chukchi Sea and Bering Strait, August 2004." *Northwestern Naturalist* 88: 168–187. doi:10.1898/1051-1733(2007)88[168:RLCOTA]2.0.CO;2.

Metcalf, V., and M. Robards. 2008. "Sustaining a Healthy Human-Walrus Relationship in a Dynamic Environment: Challenged for Comanagement." 2008. *Ecological Applications* 18, no. 2: 148-156. doi:10.1890/06-0642.1.

Mishra, U., and W. J. Riley. 2015. "Scaling Impacts on Environmental Controls and Spatial Heterogeneity of Soil Organic Carbon Stocks." *Biogeosciences* 12: 3993-4004. doi:10.5194/bg-12-3993-2015.

Moore, S. E., J. M. Grebmeier, and J. R. Davies. 2003. "Gray Whale Distribution Relative to Forage Habitat in the Northern Bering Sea : current conditions and retrospective summary." *Canadian Journal of Zoology* 81: 734–742. doi:10.1139/Z03-043.

Moore, S. E., and H. P. Huntington. 2008. "Arctic Marine Mammals and Climate Change: Impacts and Resilience." *Ecological Applications* 18, no. 2: 157-165. doi:10.1890/06-0571.1.

Moore, S. E., E. Logerwell, L. Eisner, E. V. Jr. Farley, L. A. Harwood, K. Kuletz, J. Lovvorn, J. R. Murphy, and L. T. Quakenbush. 2014. "Marine Fishes, Birds and Mammals as Sentinels of Ecosystem Variability and Reorganization in the Pacific Arctic Region." In *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment*, eds. J.M. Grebmeier and W. Maslowsik, 337-392. Dordrecht: Springer Netherlands. doi:10.1007/978-94-017-8863-2_11.

Moore, S. E., and P. J. Stabeno. 2015. "Synthesis of Arctic Research (SOAR) in Marine Ecosystems of the Pacific Arctic" *Progress in Oceanography* 60. doi:10.1016/j.pocean.2015.05.017.

Morrison, H., G. de Boer, G. Feingold, J. Harrington, M. D. Shupe, and K. Sulia. 2012. "Resilience of Persistent Arctic Mixed-phase Clouds." *Nature Geoscience* 5: 11-17. doi:10.1038/ngeo1332.

Mueter, F. J., and M. A. Litzow. 2008. "Sea Ice Retreat Alters the Biogeography of the Bering Sea Continental Shelf." *Ecological Applications* 18: 309–320. doi:10.1890/07-0564.1.

Myers-Smith, I. H., B. C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K. D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Lévesque, S. Boudreau, P. Ropars, L. Hermanutz, A. Trant, L. Siegwart Collier, S. Weijers, J. Rozema, S. A. Rayback, N. M. Schmidt, G. Schaepman-Strub, S. Wipf, C. Rixen, C. B. Ménard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf, V. Ravolainen, J. Welker, P. Grogan, H. E Epstein, and D. S. Hik.

2011. “Shrub Expansion in Tundra Ecosystems: Dynamics, Impacts and Research Priorities.” *Environmental Research Letters* 6:4 article no. 045509. doi:10.1088/1748-9326/6/4/045509.

Myers-Smith, I. H., B. K. Arnesen, R. M. Thompson, and F. Stuart Chapin III. 2006. “Cumulative Impacts on Alaskan Arctic Tundra of a Quarter Century of Road Dust.” *Ecoscience* 13: 503-510. doi:10.2980/1195-6860(2006)13[503:CIOAAT]2.0.CO;2.

National Oceanic and Atmospheric Administration. 2007. “Definitions of Ethnoecological Research Terms.” *Local Fisheries Knowledge (LFK) Project.* NOAA Fisheries National Marine Fisheries Service. www.st.nmfs.noaa.gov/lfkproject/02_c.definitions.htm.

National Petroleum Council. 2015. "Arctic Potential: Realizing the Promise of the U.S. Arctic Oil and Gas Resources." National Petroleum Council. Washington, DC. npcarcticpotentialreport.org/pdf/AR-Executive_Summary-Final.pdf

Nelson, F. E., O. A. Anisimov, and N. I. Shiklomanov. 2001. “Subsidence Risk from Thawing Permafrost.” *Nature* 410. no. 6831: 889–890. doi:10.1038/35073746.

Niebauer, H., V. Alexande, and S. M. Henrichs. 1995. "A Time-Series Study of Spring Bloom at the Bering Sea Ice Edge I. Physical Processes, Chlorophyll and Nutrient Chemistry." *Continental Shelf Research* 15: 1859–1877. doi: 10.1016/0278-4343(94)00097-7.

Noel, L. E., K. R. Parker, and M. A. Cronin. 2004. “Caribou Distribution near an Oilfield Road on Alaska's North Slope, 1978–2001.” *Wildlife Society Bulletin* 32: 757–771. http://www.academia.edu/19115003/A_Reevaluation_of_Caribou_Distribution_Near_an_Oilfield_Road_on_Alaskas_North_Slope.

Nordic Council of Ministers. 2015. “Arctic Human Development Report: Regional Processes and Global Linkages.” Nordic Council of Ministers. Copenhagen, Denmark. doi: http://dx.doi.org/10.6027/tn2014-567.

O’Donnell, J. A., M. T. Jorgenson, J. W. Harden, A. D. McGuire, M. Z. Kanevskiy, and K. P. Wickland. 2011. “The Effects of Permafrost Thaw on Soil Hydrologic, Thermal, and Carbon Dynamics in an Alaskan Peatland, Ecosystems.” *Ecosystems* 15, no. 2: 213–229. doi:10.1007/s10021-011-9504-0.

Olefeldt, D. submitted 2015. "Thermokarst Terrain: Circum Arctic Distribution and Soil Carbon Vulnerability." *Nature Geoscience*.

Overeem, I., R. S. Anderson, C. W. Wobus, G. Clow, F. E. Urban, and N. Matell. 2015. “Sea Ice Loss Enhances Wave Action at the Arctic Coast.” *Geophysical Research Letters* 38. doi:10.1029/2011GL048681.

Pastick, N. J., M. T. Jorgenson, B. K. Wylie, B. J. Minsley, L. Ji, M. A. Walvoord, B. D. Smith, J. D. Abraham, and J. R. Rose. 2013. "Extending Airborne Electromagnetic Surveys for Regional Active Layer and Permafrost Mapping with Remote Sensing and Ancillary Data, Yukon Flats Ecoregion, Central Alaska." *Permafrost and Periglacial Processes* 24, no. 3: 184-199. doi:10.1002/ppp.1775.

Pastick, N. J., M. T. Jorgenson, B. K. Wylie, J. R. Rose, M. Rigge, and M. A. Walvoord. 2014. "Spatial Variability and Landscape Controls of Near-surface Permafrost within the Alaskan Yukon River Basin." *Journal of Geophysical Research-Biogeosciences* 119, no. 6: 1244-1265. doi: 10.1002/2013JG002594.

Pauktuutit Inuit Women of Canada. 2006. “National Strategy to Prevent Abuse in Inuit Communities *and* Sharing Knowledge, Sharing Wisdom.” Ottawa, Canada.

wwwpauktuutit.ca/wp-content/blogs.dir/1/assets/InuitStrategy_e.pdf

Pearce, T., J. Ford, A. C. Willox, and B. Smit. 2015. “Inuit Traditional Ecological Knowledge (TEK), Subsistence Hunting and Adaptation to Climate Change in the Canadian Arctic.” *Arctic* 68, no. 2: 233-245. doi:10.14430/arctic4475.

Perovich, D. K., W. Meier, M. Tschudi, S. Farrell, S. Gerland, and S. Hendricks. 2015. “Sea Ice.” *Arctic Report Card: Update for 2015, Tracking Recent Environmental Changes.* www.arctic.noaa.gov/reportcard/sea_ice.html

Perrette, M., A. Yool, G. D. Quartly, and E. E. Popova. 2011. "Near-ubiquity of Ice-edge Blooms in the Arctic." *Biogeosciences* 8: 515–524. doi:10.5194/bg-8-515-2011.

Pistone, K., I. Eisenman, and V. Ramanathan. 2014. "Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice." Proceedings of the National Academy of Sciences of the United States of America 11. doi/10.1073/pnas.1318201111.

Post, E., U. S. Bhatt, C. M. Bitz, J. F. Brodie, T. L. Fulton, M. Hebblewhite, J. Kerby, S. J. Kutz, and I.

Walker. 2013. "Ecological Consequences of Sea-Ice Decline." *Science* 341: 519-524. doi:10.1126/science.123522.

Quinn, P. K., T. S. Bates, E. Baum, N. Doubleday, A. M. Fiore, M. Flanner, A. Fridlind, T. J. Garrett , D. Koch, S. Menon, D. Shindell, A. Stohl, and S. G. Warren. 2008. "Short-lived Pollutants in the Arctic: Their Climate Impact and Possible Mitigation Strategies." *Atmospheric Chemistry and Physics* 8: 1723-1735. www.atmos-chem-phys.net/8/1723/2008/.

Rand, K. M., and E. A. Logerwell. 2011. "The First Demersal Trawl Survey of Benthic Fish and Invertebrates in the Beaufort Sea since the Late 1970s." *Polar Biology* 34: 475–488. doi:10.1007/s00300-010-0900-2.

Randerson, J. T., H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, and C. S. Zender. 2006. "The Impact of Boreal Forest Fire on Climate Warming." *Science* 314: 1130-1132. doi:10.1126/science.1132075.

Ray, C. G., G. L. Hufford, J. E. Overland, I. Krupnik, J. McCormick-Ray, K. Frey, and E. Labunski. 2016. "Decadal Bering Sea Seascape Change: Consequences for Pacific Walruses and Indigenous Hunters." *Ecological Applications* 26: 24-41. doi:10.1890/15-0430.1.

Reading, C .L., and F. Wien. 2009. "Health Inequalities and Social Determinants of Aboriginal Peoples' Health." National Collaborating Centre for Aboriginal Health. Prince George, British Columbia. http://ahrnets.ca/files/2011/02/NCCAH-Loppie-Wien_Report.pdf.

Reid, P. C., D. G. Johns, M. Edwards, M. Starr, M. Poulin, and P. Snoeijs. 2007. "A Biological Consequence of Reducing Arctic Ice Cover: Arrival of the Pacific Diatom *Neodenticula Seminae* in the North Atlantic for the First Time in 800 000 Years." *Global Change Biology* 13: 1910–1921. doi:10.1111/j.1365-2486.2007.01413.x.

Richman, S., and J. Lovvorn. 2003. "Effects of Clam Species Dominance on Nutrient and Energy Acquisition by Spectacled Eiders in the Bering Sea." *Inter-Research Marine Ecology Progress Series* 261: 283–297. doi:10.3354/meps261283.

Rocha, A. V., M. M. Loranty, P. E. Higuera, M. C. Mack, F. Sheng Hu, B. M. Jones, A. L. Breen, E. B. Rastetter, S. J. Goetz, and G. R. Shaver. 2012. "The Footprint of Alaskan Tundra Fires during the Past Half-century: Implications for Surface Properties and Radiative Forcing." *Environmental Research Letters* 7, no. 4. doi:10.1088/1748-9326/7/4/044039.

Rode, K. D., E. V. Regehr, D. C. Douglas, G. Durner, A. E. Derocher, G. W. Thiemann, and S. M. Budge. 2014. "Variation in the Response of an Arctic Top Predator Experiencing Habitat Loss: Feeding and Reproductive Ecology of Two Polar Bear Populations." *Global Change Biology* 20: 76–88. doi:10.1111/gcb.12339.

Romanovsky, V. E., S. L. Smith, and H. H. Christiansen. 2010. "Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007–2009: a Synthesis." *Permafrost Periglacial Processes* 21, no. 2: 106–116. doi:10.1002/ppp.689.

Romanvosky, V. E., S. L. Smith, H. H. Christiansen, N. I. Shiklomanov, D. A. Streletskiy, D. S. Drozdov, N. G. Oberman, A. L. Kholodov, and S. S. Marchenko. 2012. "2012: Permafrost." *Arctic Report Card 2012*. http://www.arctic.noaa.gov/reportcard.

Ruscio, B. A., M. Brubaker, J. Glasser, W. Hueston, and T. W. Hennessy. 2015. "One Health: A Strategy for Resilience in a Changing Arctic." *International Journal of Circumpolar* Health 74: 27913. www.circumpolarhealthjournal.net/index.php/ijch/article/view/27913.

Schur, Y. L., and M. T. Jorgenson. 2007. “Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems.” *Permafrost Periglacial Processes* 18, no. 1: 7-19. doi: 10.1002/ppp.582.

Schuur, E. A. G., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G.. Vogel, and S. A. Zimov. 2008. “Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle.” *BioScience* 58, no. 8: 701–714. doi:10.1641/B580807.

Schuur, E. A. G., A. D. McGuire, C. Schädel, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E. Romanovsky, K. Schaefer, M. R. Turetsky, C. C. Treat, and J. E. Vonk. 2015. "Climate Change and the Permafrost Carbon Feedback." *Nature* 520, no. 7546: 171-179. doi:10.1038/nature14338.

Serreze, M., and R. G. Barry. 2011. "Processes and Impacts of Arctic Amplification: A Research Synthesis." *Global and Planetary Change* 77: 85-96. doi:10.1016/j.gloplacha.2011.03.004.

Shepherd, A., E. R. Ivins, A. Geruo, V. R. Barletta, M. J. Bentley, S. Bettadpur, K. Briggs, D. H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M. A. King, J. T. M. Lenaerts, J. Li, S. R. F. Litgenberg, A. Luckman, A. B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mougino, A. Muir, J. P. Nicolas, J. Paden, A. J. Payne, H. Pritchard, E. Rignot, H. Rott,, L. S. Sorenson, T. A. Scambos, B. Scheuchl, E. J. O. Schrama, B. Smith, A. V. Sundal, J. H. van Angelen, W. J. Van de Berg, M. R. van den Broeke, D. G. Vaughan, I. Velicogna, J. Wahr, P. L. Whitehouse, D. J. Wingham, D. Yi, D. Young, and H. J. Zwally. 2012. “A Reconciled Estimate of Ice-Sheet Mass Balance.” *Science* 30, no. 338: 1183-1189; doi:10.1126/science.1228102.

Shupe, M. D. 2011. "Clouds at Arctic Atmospheric Observatories, Part II: Thermodynamic Phase Characteristics." *Journal of Applied Meteorology and Climatology* 50: 645-661. doi:10.1175/2010JAMC2468.1.

Shur, Y . L., and M. T. Jorgensen. 2007. "Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems." *Permafrost and Periglacial Processes* 18: 7-19. doi10.1002/ppp.582.

Silber, G.K., M. Lettrich, and P.O. Thomas (eds.). 2016. “Report of a Workshop on Best Approaches and Needs for Projecting Marine Mammal Distributions in a Changing Climate.” (Technical Memorandum, 2016). U.S. Department of Commerce, NOAA. Santa Cruz, California.

Stephenson, S. R., and L. C. Smith. 2015. "Influence of Climate Model Variability on Projected Arctic Shipping Futures." *Earth's Future* 3: 331-343. doi:10.1002/2015EF000317.

Stolarski, J. T. "Growth and Energetic Condition of Dolly Varden Char in Coastal Arctic Waters." (Ph.D. Diss., 2015, Univ. Alaska Fairbanks).

Stroeve, J., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier. 2012. “Trends in Arctic Sea Ice Extent from CMIP5, CMIP3 and Observations.” *Geophysical Research Letters* 39. doi:10.1029/2012GL052676.

Sundqvist, L., T. Harkonen, C. J. Svensson, and K. C. Harding. 2012. “Linking Climate Trends to Population Dynamics in the Baltic Ringed Seal: Impacts of Historical and Future Winter Temperatures.” *Ambio* 41 no. 8: 865-872. doi: 10.1007/s13280-012-0334-x

Sweeney, C., E. Dlugokencky, C. E. Miller, S. Wofsy, A. Karion, S. Dinardo, R. Y.-W. Chang, J. B. Miller, L. Bruhwiler, A. M. Crotwell, T. Newberger, K. McKain, R. S. Stone, S. E. Wolter, P. E. Lang, and P. Tans. 2016: “No Significant Increase in Long-term CH_4 Emissions in North Slope of Alaska Despite Significant Increase in Air Temperature.” *Geophysical. Research Letters.* doi:10.1002/2016GL069292.

Tape, K.D., D. D. Gustine, R. W. Ruess, L. G. Adams, and J. A. Clark. 2016. “Range Expansion of Moose in Arctic Alaska Linked to Warming and Increased Shrub Habitat” *PLoS ONE* 11: e0152636. doi:10.1371/journal.pone.0152636.

Tebaldi, C., B. H. Strauss, and C. S. Zervas. 2012. "Modelling Sea Level Rise Impacts on Storm Surges Along US Coasts." *Environmental Research Letters* 7: 1-11. doi:10.1088/1748-9326/7/1/014032.

Thomson, J., and W. E. Rogers. 2014. "Swell and Sea in the Emerging Arctic Ocean." *Geophysical Research Letters* 41: 3136–3140. doi:10.1002/2014GL059983.

Timmermans, M. L., and A. Proshutinsky. 2015. Sea Surface Temperature. "Arctic Report Card: Update for 2015, Tracking Recent Environmental Changes." www.arctic.noaa.gov/reportcard/sea_ice.html.

Tremblay, J. É., D. Robert, D. E. Varela, C. Lovejoy, G. Darnis, R. J. Nelson, and A. R. Sastri. 2012. "Current State and Trends in Canadian Arctic Marine Ecosystems: I. Primary Production." *Climate Change* 115: 161–178. doi:10.1007/s10584-012-0496-3.

Tremblay, J. É., L. G. Anderson, P. Matrai, P. Coupel, S. Bélanger, C. Michel, and M. Reigstad. 2015. "Global and Regional Drivers of Nutrient Supply, Primary Production and CO_2 Drawdown in the Changing Arctic Ocean." *Progress in Oceanography* 139: 171-196. doi:10.1016/j.pocean.2015.08.009.

U.S. Navy. 2014. "U.S. Navy Arctic Roadmap, 2014-2030." U.S. Navy. Washington, DC. www.navy.mil/docs/USN_arctic_roadmap.pdf.

Udevitz, M.S., R. L. Taylor, J. L. Garlich-Miller, L. T. Quakenbush, and J. A. Snyder. 2013. "Potential Population-level Effects of Increased Haulout-related Mortality of Pacific Walrus Calves." *Polar Biology* 36: 291–298. doi:10.1007/s00300-012-1259-3.

U.S. Arctic Research Commission. 2015. "Report on the Goals and Objectives for Arctic Research 2015-2016." USA: US Arctic Research Commission. https://storage.googleapis.com/arcticgov-static/publications/goals/usarc_goals_2015-2016.pdf.

United States Coast Guard. 2013. "Arctic Strategy." Washington, DC: United States Coast Guard. www.uscg.mil/seniorleadership/docs/cg_arctic_strategy.pdf.

Van Everdingen, R. O. 1998, revised 2005. "Multi-Language Glossary of Permafrost and Related Ground-Ice Terms in Chinese, English, French, German, Icelandic, Italian, Norwegian, Polish, Romanian, Russian, Spanish, and Swedish." International Permafrost Association Terminology Working Group. http://globalcryospherewatch.org/reference/glossary_docs/Glossary_of_Permafrost_and_Ground-Ice_IPA_2005.pdf.

Vermaire, J. C., M. F. J. Pisaric, J. R. Thienpont, C. J. Courtney Mustaphi, S. V. Kokelj, and J. P. Smol. 2014. "Arctic Climate Warming and Sea Ice Declines Lead to Increased Storm Surge Activity." *Geophysical Research Letters* 39. doi:10.1002/grl.50191.

Viereck, L. "Ecological Effects of River Flooding and Forest Fires on Permafrost in the Taiga of Alaska." 1973. (Paper presented at Permafrost: The North American Contribution to the Second International Conference. Yakutsk, USSR).

von Biela, V. R., C. E. Zimmerman, and L. L. Moulton. 2011. "Long-term Increases in Young-of-the-year Growth of Arctic Cisco Coregonus Autumnalis and Environmental Influences." *Journal of Fish Biology* 78: 39–56. doi:10.1111/j.1095-8649.2010.02832.x.

Vonk, J. E., S. E. Tank, W. B. Bowden, I. Laurion, W. F. Vincent, P. Alekseychik, M. Amyot, M. F. Billet, J. Canário, R. M. Cory, B. N. Deshpande, M. Helbig, M. Jammet, J. Karlsson, J. Larouche, G. MacMillan, M. Rautio, K. M. Walter Anthony, K. P. and Wickland. 2015. "Reviews and Syntheses: Effects of Permafrost Thaw on Arctic Aquatic Ecosystems." *Biogeosciences* 12, no. 23: 7129–7167. doi:10.5194/bg-12-7129-2015.

Wadham, J. L., J. Hawkings, J. Telling, D. Chandler, J. Alcock, E. Lawson, P. Kaur, E. A. Bagshaw, M. Tranter, A. Tedstone, and P. Nienow. 2016. "Sources, Cycling and Export of Nitrogen on the Greenland Ice Sheet" (Discussion paper under review for the journal *Biogeosciences,* 2016). doi:10.5194/bg-2015-484.

Walker D. A., and J. L. Peirce. 2015. “Rapid Arctic Transitions Due to Infrastructure and Climate (RATIC): A Contribution to ICARP III.” Alaska Geobotany Center, University of Alaska Fairbanks. Fairbanks, Alaska. www.geobotany.uaf.edu/library/pubs/WalkerDAed2015-RATICWhitePaper-ICARPIII.pdf.

Walker, H. J., and P. F. Hudson. 2003. "Hydrologic and Geomorphic Processes in the Colville River Delta, Alaska." *Geomorphology* 56, no. 3-4: 291-303. doi:10.1016/S0169-555X(03)00157-0.

Weijer, W., M. E. Maltrud, M. W. Hecht, H. A. Dijkstra, and M. A. Kliphuis. 2012. “Response of the Atlantic Ocean Circulation to Greenland Ice Sheet Melting in a Strongly-eddying Ocean Model.” *Geophysical Research Letters* 39. doi:10.1029/2012GL051611.

Whitehouse, G.A., K. Aydin, T. E. Essington, and G. L. Jr. Hunt. 2014. “A Trophic Mass Balance Model of the Eastern Chukchi Sea with Comparisons to other High-latitude Systems.” *Polar Biology* 37: 911-939. doi:10.1007/s00300-014-1490-1.

Wiese, F. K., R. Merrick, G. Auad, D. Williams, P. Stabeno, and B. Kelly. Strawman Conceptual Ecosystem Model for the Chukchi and Beaufort Seas: Discussion White paper. In “Developing a Conceptual Model of the Arctic Marine Ecosystem” (Paper presented at professional workshop, Washington, D.C., April 30 – May 2, 2013). www.nprb.org/assets/images/uploads/ArcticConceptualModelingReport_final_lowres.pdf.

Yue, X., L. J. Mickley, J. A. Logan, R. C. Hudman, M. V. Martin, and R. M. Yantosca. 2015. "Impact of 2050 Climate Change on North American Wildfire: Consequences for Ozone Air Quality." *Atmospheric Chemistry and Physics* 15: 10033-10055. doi:10.5194/acp-15-10033-2015.

Zhang, J., R. Lindsay, A. Schweiger, and I. Rigor. 2012. “Recent Changes in the Dynamic Properties of Declining Arctic Sea Ice: A Model Study.” *Geophysical Research Letters* 39. doi:10.1029/2012GL053545.

Abbreviations

AAAS	American Association for the Advancement of Science
AAPC	Alaska Arctic Policy Commission
ABoVE	Arctic-Boreal Vulnerability Experiment
ACCAP	Alaska Center for Climate Assessment and Policy
ACCER	Alaska Climate Change Executive Roundtable
ACE	Arctic Collaborative Environment
ACEs	Adverse Childhood Experiences
ACF	Administration for Children and Families
ACLIM	Alaska Climate change Integrated Modeling project
ACME	Accelerated Climate Modeling for Energy
ADAC	The Arctic Domain Awareness Center
ADEC	Alaska Department of Environmental Conservation
ADIWG	Alaska Data Integration Working Group
AEA	Alaska Energy Authority
AERONET	Aerosol Robotic Network
AESC	Arctic Executive Steering Committee
AFC	Alaska Fire Consortium or Alaska Fisheries Center
AHRQ	Agency for Healthcare Research and Quality
AIDA	American Indian Development Associates
AIFC	Arctic Information Fusion Capability
ALCC	Arctic Landscape Conservation Cooperative
AMAP	Arctic Monitoring and Assessment Programme
AMBON	Arctic Marine Biodiversity Observation Network
AMOS	Arctic Mobile Observing System
AMSR2	Advanced Microwave Scanning Radiometer 2
ANTHC	Alaska Native Tribal Health Consortium
AOOS	Alaska Ocean Observing System
Arctic-FROST	Arctic Frontiers of Sustainability
ARM	Atmospheric Radiation Measurement
ARPA	Arctic Research and Policy Act
ASAMM	Aerial Surveys of Arctic Marine Mammals

ASR	Atmospheric Systems Research
AToM	Atmospheric Tomography Mission
BIA	Bureau of Indian Affairs
BIE	Bureau of Indian Education
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CBRAT	Coastal Biodiversity Risk Analysis Tool
CCHRC	Cold Climate Housing Research Center
CDC	Centers for Disease Control
CDI	Climate Data Initiative
CENRS	Committee on the Environment, Natural Resources and Sustainability
CERES	Clouds and the Earth's Radiant Energy System
CESM	Community Earth System Model
CISM	Community Ice Sheet Model
CLIVAR	Climate Variability and Predictability
CMIP	Coupled Model Intercomparison Project
CRREL	Cold Regions Research and Engineering Laboratory
CRT	Climate Resilience Toolkit
DBO	Distributed Biological Observatory
DHS	Department of Homeland Security
DLR	German Aerospace Center
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOJ	Department of Justice
DOL	Department of Labor
DOS	Department of State
DOT	Department of Transportation
EDA	Economic Development Administration
EPA	Environmental Protection Agency

ERMA	Environmental Response Management Application
ESRL	Earth System Research Laboratory
FAA	Federal Aviation Administration
FWS	Fish and Wildlife Service
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GLISN	Greenland Ice Sheet Monitoring Network
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GWP	Global Warming Potential
HHS	Health and Human Services
HRSA	Health Resources and Services Administration
HUD	United States Department of Housing and Urban Development
IARPC	Interagency Arctic Research Policy Committee
IASC	International Arctic Science Committee
IASOA	International Arctic System for Observing the Atmosphere
ICC	Inuit Circumpolar Council
ICESat-2	Ice, Cloud, and land Elevation Satellite 2
IGAC	International Global Atmospheric Chemistry
IHS	Indian Health Services
IK	Indigenous Knowledge
I-LEAD	Initiative for Leadership, Empowerment, and Development
IPCC	Intergovernmental Panel on Climate Change
ISMIP6	Ice Sheet Model Intercomparison Project for CMIP6
ISRO	Indian Space Research Organization
ISSM	Ice Sheet System Model
LC	Library of Congress
LCCs	Landscape Conservation Cooperative
LK	Local Knowledge
LEO	Local Environmental Observer
LIVV	Land Ice Verification and Validation
LMEs	Large Marine Ecosystems
MAAT	Mean Annual Air Temperature
MMC	Marine Mammal Commission

MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate-resolution Imaging SpectroRadiometer
MOM	Alaska Native Maternal Organics Monitoring Study
MOSAiC	Multi-disciplinary Drifting Observatory for the Study of Arctic Climate
MPL	Micro-Pulse Lidar
NASA	National Aeronautics and Space Administration
NBS	National Baseline Study
NCHS	National Center for Health Statistics
NDACC	Network for the Detection of Atmospheric Composition Change
NESDIS	National Environmental Satellite, Data, and Information Service
NGA	National Geospatial-Intelligence Agency
NGEE-Arctic	Next Generation Ecosystem Experiment-Arctic
NGOs	Non-governmental Organizations
NIC	National Ice Center
NIFA	National Institute of Food and Agriculture
NIH	National Institutes of Health
NIJ	National Institute of Justice
NIMH	National Institute on Mental Health
NIMHD	National Institute on Minority Health and Health Disparities
NIOSH	National Institute for Occupational Safety and Health
NISAR	NASA-ISRO Synthetic Aperture Radar
NOAA	National Oceanic and Atmospheric Administration
NOC	National Ocean Council
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NRL	Naval Research Laboratory
NSAR	National Strategy for the Arctic Region
NSF	National Science Foundation
NSSI	North Slope Science Initiative
NSTC	National Science and Technology Council
NTSB	National Transportation Safety Board
NWS	National Weather Service
OAR	Ocean and Atmospheric Research

OIB	Operation IceBridge
OJJDP	Office of Juvenile Justice and Delinquency Prevention
OMG	Oceans Melting Greenland
OMI	Ozone Monitoring Instrument
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OSH	Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
OVC	Office for Victims of Crime
OVW	Office on Violence Against Women
PACES	air Pollution in the Arctic: Climate, Environment, and Societies
PAG	Pacific Arctic Group
PARMA	Pacific Arctic Regional Marine Assessment
POPs	Persistent Organic Pollutants
RAMP	Rural Alaska Monitoring Program
RTI International	Formerly Research Triangle Institute
SAMHSA	Substance Abuse and Mental Health Services Administration
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic Aperture Radar
SCAN	Soil Climate Analysis Network
SEARCH	Study of Environmental Arctic Change
SI	Smithsonian Institutes
SIRTA	Systematic Improvements to Reanalysis of the Arctic
SMOS	Soil Moisture and Ocean Salinity
SNOTEL	Snow Telemetry
SODA	Stratified Ocean Dynamics of the Arctic
SOST	Subcommittee on Ocean Science and Technology
UAF	University of Alaska Fairbanks
US AON	U.S. Arctic Observing Network
USACE	U.S. Army Corps of Engineers
USARC	U.S. Arctic Research Commission
USCG	U.S. Coast Guard

USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
US IABP	U.S. Interagency Arctic Buoy Program
VIIRS	Visible Infrared Imaging Radiometer Suite
VPSO	Village Public Safety Officers
WALRUS	Walrus Adaptability and Long-term Responses
WASH	Arctic Water, Sanitation and Hygiene
WIHAH	Water Innovations for Healthy Arctic Homes