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Introduction

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The Arctic and IARPC

The Arctic region touches the lives of all Americans.[1] 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 in Alaska and throughout the Arctic with consequences for people around the world.

Created by Congress[2] 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 16 Federal agencies[3] and collaboration with outside partners through its implementation structure—IARPC Collaborations.[4] 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,[5] numerous dramatic environmental events have astonished Arctic observers. These include record-breaking warm air temperatures and end-of-summer minimum sea ice extent, an extreme melting event 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% and 2.6% 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.

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[1] 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

[2] 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

[3] Appendix 1

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

[5] "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

The consequences of sea ice retreat exemplify a system of interactions and feedbacks that amplify Arctic warming. These urge stakeholders 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** to advance holistic understanding and support science-based policy decisions.

A complete understanding of the Arctic System must include a 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,*[6] which, at the request of IARPC, looked 10 to 20 years into the future of Arctic research to make inquiry more targeted and effective. This is also highlighted in the growing role for social science in Arctic research, as recommended by the U.S. Arctic Research Commission (USARC) in its 2015 report on goals and objectives.[7]

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 permafrost, sea ice, and glacier processes. 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.

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 opportunity, and the cultural vibrancy of native and other Arctic residents;

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

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

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 the potential response to 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 defense and emergency response agencies have skillful forecasts of 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*). Information will recognize 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*[8] and its implementation through the *National Strategy for the Arctic Region* (NSAR).[9]

Guiding Principles

Research planning and coordination in support of these **policy drivers** follows some important **guiding principles**. These include support for (1) a portfolio of basic and applied disciplinary research, and broader systems-level, research-based modelling and synthesis; (2) a set of sustained measurements supporting long-term observations and the understanding of Arctic System changes, and mechanisms to provide timely and efficient access to data; (3) the inclusion of Indigenous Knowledge[10] holders and northern residents versed in Local Ecological Knowledge[11] as generators of and participants in research; and (4) international collaborations that strengthen research, provide opportunities for improved access to the Arctic, and make the most effective use of costly infrastructure and logistics.

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 goals in the previous IARPC Plan.[12] Two holistic goals integrate understanding of components

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

[9] *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

[10] 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.

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

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

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 **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 mountain **glaciers 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 and natural and built environments;
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, and possibly international, research efforts; and **Performance Elements**—tasks with concrete, measurable outcomes that demonstrate progress made 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**," those that assist the Lead Agency and whose research contributes to the implementation and reporting. Some Performance Elements have only one agency (e.g., 3.1.3 and 3.1.4 are NASA-only projects), but they generate data that are used by multiple agencies and the researchers they support.

Implementation

This Plan builds upon its predecessor, *Arctic Research Plan FY13-17*, whose successes are highlighted in the IARPC biennial report.[13] This Plan's successful implementation will depend on the collaborative infrastructure, IARPC Collaborations, 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 partners from state and local governments, academic institutions, non-government organizations (NGOs), and community members. People from these

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[13] "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

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. 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. 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 partnership. 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.

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

Authors: Roberto Delgado (NIMH), Tom Hennessy (CDC), Cheryl Rosa (USARC)

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 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.

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 animal migration patterns, ocean acidification, and sea level rise. Further, many Arctic populations are also experiencing heritage and language loss, shifting economies, and population migration as well. Stakeholders 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, and cultural and linguistic vitality.

A coordinated, evidence-based, governmentwide plan can help to 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 incorporate LEK and IK into science and research and to use this community-based knowledge 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, this 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. Recognizing that human health, animal health, and ecosystem health are inextricably linked, particularly in subsistence communities, it is vital to establish a network of diverse stakeholder 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 partnership 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: CDC, DOI (FWS, USGS), EPA, NOAA, USDA (NIFA), DOS

Performance Element 1.1.2: In partnership with the ANTHC, support community-based monitoring and IK and LEK 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

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 Persistent Organic Pollutants (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: CDC, EPA

Performance Element 1.1.4: Increase understanding of how both natural climate change and the effects of human impacts 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), SI, NASA, NOAA, NSF, USDA (NIFA)
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, 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: EPA, CDC, DOI (FWS), NOAA

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.

***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 partnership 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: CDC, USARC, EPA, USDA, IHS, 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: CDC, EPA, HUD

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: SI, DOE, LC, NASA, NOAA, NSF
Supporting Agency: DOI (NPS)

Performance Element 1.2.4: Through the Arctic-FROST[14] 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 young, Indigenous scholars 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: 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.

Lead Agencies: DOI (BOEM), NSF

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

Performance Element 1.3.2: In partnership 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: CDC, DOS, EPA, IHS, USARC, USDA

Performance Element 1.3.3: Together with the Alaska Energy Authority (AEA), the Cold Climate Housing Research Center (CCHRC), and the University of Alaska, Fairbanks, promote research on renewable and efficient energy systems 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 our 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 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 NSB 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)

Performance Element 1.4.3: Together with the American Indian Development Associates, 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: HHS (ACF), Dept. of Education, DOI (BIE), 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.

Lead Agencies: CDC, DOS, NIH (NIMH, NIMHD), SAMHSA, USARC

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: CDC (NCHS), 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: Alaska has historically 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: CDC (NIOSH), FAA, NTSB, OSHA, USCG

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: CDC (NIOSH), USCG, FAA, NTSB, OSHA

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 partnership 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

Authors: Ashley Williamson (DOE), Allison McComiskey (NOAA)

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; meridional (north-south) heat transport; and radiative forcing of atmospheric constituents such as clouds, aerosols, and gases, coupled with changing surface properties; drive this enhanced warming. Conversely, changes in Arctic conditions may impact circulations that change weather and climate patterns over the Northern Hemisphere (Cohen et al. 2014) and beyond.

Advancing an integrated understanding of atmospheric processes and the resulting radiative forcing in the Arctic is required to address all IARPC policy drivers. 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 defense and emergency response 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 increased biomass burning in the Arctic and at lower latitudes, causing air quality problems (*Well-being*) for Arctic residents (Kasischke et al. 2010).

The atmosphere couples 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 coupled to several of the 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 energetic and mass fluxes across the Arctic is essential for understanding the future state of Arctic weather and climate. But a paucity of observations over the different Arctic 'domains' or 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. Aerosol 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 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, Arctic clouds have a limited ability to cool the surface by reflecting solar energy, but cloud infrared radiation significantly warms the surface year round (Intrieri et al. 2002). As a result, the net 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 (Garret et al. 2009) 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).

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). As a greenhouse gas, methane is approximately 20 times more effective at trapping heat than is carbon dioxide. Understanding current methane emissions and potential scenarios under a warmer Arctic is imperative. Many global circulation models do not take into account carbon feedback loops from Arctic tundra, where warming causes carbon release from thawing and decomposing tundra that 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.

This Research Goal is focused 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.

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 climate system—e.g., ocean, sea ice, and permafrost. Closing the surface energy budget over different "domains" or 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 are currently inadequate 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 Agency: DOE
Supporting Agencies: NSF, NOAA, DOD (ONR)

Performance Element 2.1.2: Improve uniformity and accessibility of surface radiative and heat flux information from Unmanned Aerial Systems (UAS), satellite retrievals, 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

Research Objective 2.2. Improve understanding of the composition of the Arctic atmosphere – moisture, clouds, precipitation, aerosols, and gases—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 detailed in situ 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. Characterizing the vertical structure of atmospheric constituents, achievable through manned and unmanned aircraft programs, ground-based observations, and satellite measurements, is critical in determining how and when the different constituents interact and their radiative effects.

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., NOAA Global Monitoring Division Barrow Observatory, Study for Environmental Arctic Change (SEARCH), and NASA Aerosol Robotic Network (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 Agency: NASA

Performance Element 2.2.2: Continue support for and planning of aircraft missions—e.g., NASA Atmospheric Tomography Mission (ATom) and air Pollution in the Arctic: Climate, Environment, and

Societies[15] (PACES)—that contribute observations of atmospheric composition and relevant processes such as transport, deposition, and radiation.

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

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., Network for the Detection of Atmospheric Composition Change (NDACC)), together with new measurements (especially UAS) in underrepresented Arctic regions. Develop a better understanding of the representative nature of fixed sites by characterizing the range of conditions that exist across the Arctic through synthesis activities such as IASOA working groups.

Lead Agency: NOAA
Supporting Agencies: DOE, NASA

Performance Element 2.2.4: In collaboration with efforts described under the Permafrost Goal, use existing observation syntheses of atmospheric carbon to provide a measurement gap analysis that supports 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 Agency: DOE

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 Artic 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 produced or removed from the atmosphere. Of particular interest due to the associated radiative forcing potential, is understanding and representing the controls on cloud phase, which feeds 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—e.g., the NASA AERONET and CALIOP satellite sensors—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.

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[15] http://www.igacproject.org/PACES

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

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; interactions with aerosol, and lead to advancement in representing clouds in models at many scales.

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

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: NSF, NOAA

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

Authors: Martin O. Jeffries (OSTP), Walter N. Meier (NASA)

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 heat 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.

The Arctic sea ice cover is changing. The end-of-summer minimum sea ice extent and the end-of-winter maximum sea ice extent are decreasing at rates of 13.4% per decade and 2.6% per decade, respectively (Perovich et al. 2015). 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); 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 (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 also fueling speculation about growing ship traffic (cargo, tourism) and development of natural resources (oil and gas, minerals, fisheries). Any growth in such activities has, in turn, implications for homeland and national security, e.g., search and rescue, oil spill preparedness and response, domain awareness, and defense readiness. Current model projections of sea ice extent show that an 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). Nevertheless, the projections imply continuing growth in commercial interest and a documented need for homeland and national security responses that are informed by science and technology (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 the impacts extend 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 (daily, weekly, seasonal, inter-annual, decadal).

Rationale: Sea ice thickness, extent, and volume are key descriptors of the state (health) 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 a program of investigator-driven observations and process studies of the pack ice (e.g., ice thickness distribution, topography 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 Agency: NSF
Supporting Agencies: DOD (ONR), DOI (BOEM), NASA, NOAA

Performance Element 3.1.2: Continue to support the U.S. Interagency Arctic Buoy Program to provide meteorological, ice, and oceanographic data for research purposes and to meet real-time operational requirements. The U.S. Interagency Arctic Buoy Program, 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: DOD (Navy), DHS (USCG), NOAA (NESDIS)
Supporting Agencies: DOD (ONR), NASA, NOAA (OAR), NSF

Performance Element 3.1.3: Continue Operation IceBridge to measure sea ice freeboard and thickness, and 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 the ICESat-2 satellite in 2018 to estimate sea ice thickness over the entire Arctic Ocean and adjacent seas, and, in conjunction with the overlapping Operation IceBridge mission, validate the satellite measurements and the algorithms that convert those measurements into sea ice thickness.

Lead Agency: NASA

Performance Element 3.1.5: Use multiple remote sensing data sets to (a) investigate sea ice properties and processes, and atmosphere-ice-ocean interactions; and (b) 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), NASA, NOAA, 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 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 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), NASA, NOAA, 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), NASA, NOAA, 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., the 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, e.g., 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 reduce uncertainty and enhance prediction capability at a range of spatial and temporal scales.

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

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

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 validation and verification; and evaluation of model skill.

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

Research Objective 3.3. Support collaborative networks of researchers 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 and information to a broader audience.

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 a broader audience.

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

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

Authors: Candace Nachman (NOAA), Guillermo Auad (BOEM), Sue Moore (NOAA), Vanessa von Biela (USGS)

In the changing Arctic, improved understanding of ecosystem structure and function offers many benefits and is needed to address several IARPC policy drivers. For example, it reduces uncertainty for decision makers charged with environmental stewardship (*Stewardship*). Improved ecosystem 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; Renner et al. 2014; Grebmeier and Maslowski 2014). Understanding these changes and their role in the climate system are crucial to improve the understanding of the Arctic marine ecosystems role as a component of planet Earth (*Arctic-Global Systems*).

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).

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 important consequences for population trajectory stemming from increased mortality risks on land (Udevitz et al. 2013). Reduced sea ice has also been associated with reduced foraging, poorer body condition, and reduced reproduction of polar bears in the southern Beaufort Sea (Rode et al. 2014).

Relationships of whales and ice-dependent seals with loss of sea ice are less clear (Moore and Huntington 2008; Silber et al. 2016), as are the effects of these changes on Indigenous communities that depend upon 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 compared with subarctic ecosystems (Whitehouse et al. 2014).

The following 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 integrable 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 objective will benefit from interagency collaboration because of multi-agency jurisdiction of Arctic marine species and the need of 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.

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

Performance Element 4.1.2: Continue studies to document Arctic marine species biodiversity (e.g. Arctic Marine Biodiversity Observing Network and Loss of Sea Ice programs) and habitat use in the Arctic. Ensure datasets will be available through open access data portals.

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

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 underwater vehicles equipped with sensors capable of recording marine mammal vocalizations.

Lead Agencies: NOAA, DOI (USGS, BOEM)
Supporting Agencies: DOI (FWS), 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 objective will benefit from engagement with Indigenous subsistence communities through co-management agreements, as 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 partners.

Performance Element 4.2.1: Assess feeding ecology of Arctic species and fill seasonal data gaps.

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

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

Lead Agencies: NOAA, DOI (USGS, BOEM)

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: DOI (BOEM), NSF, DOD (ONR), USARC
Supporting Agencies: NOAA, DOI (FWS), 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[16] (DBO) sampling in regions 1-5 and make data publicly available through upload of metadata to the Earth Observing Laboratory/DBO data portal.

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

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

Performance Element 4.3.3: Build connections between DBO and PAG marine research activities with existing community-based observation programs, and encourage data sharing.

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

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.

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

Performance Element 4.3.5: Implement the Regional Action Plan for Southeastern Bering Sea Climate Science[17] 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.

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

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. On-going 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: DOI (USGS), NSF, DOD (ONR)

[17] The Alaska Regional Action Plans, through ecosystem-based fishery management, 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.

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

Authors: Charles E. Webb (NASA), Wm. J. Wiseman, Jr. (NSF)

Global mean sea level is estimated to have risen by 1.2 to 1.9 mm per year over the 20th century (Hay et al. 2015) 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% of the observed sea level rise appears 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, which increase melting on ice surfaces, and warmer ocean temperatures, which 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 characterizing the current state of land ice, important questions remain in understanding 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 implications for homeland and national security. The altered coastal currents will impact transport processes, such as spill response and search and rescue operations. Coastal infrastructure built near the coast, such as cities with associated gravity-fed sewage systems or subways as well as ports and military installations, can be damaged by storm surge. In addition to the economic and defense costs, the potential for loss of life is even more important.

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 space and time scales. These processes are strongly influenced by the atmosphere above, the ocean adjacent to or below, 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 examines the interactions and feedbacks among the land ice, atmosphere, ocean, and solid earth.

The Glaciers 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 the 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. The 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.

Performance Element 5.1.1: Maintain support for aircraft and satellite missions that contribute to long-term observations of land ice. The NASA Operation IceBridge and ICESat-2 missions and the USGS Landsat-8 mission are examples of contributions to this performance element.

Lead Agency: NASA
Supporting Agency: 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 time and space scales. The NASA Operation IceBridge mission and the USGS Benchmark Glaciers Program in Alaska are examples of contributions to this performance element.

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

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, glacial isostatic adjustment, iceberg melting and surface energy balance and observations. Feedbacks from and to, and interactions with, other parts of the Arctic System require linkages with other parts of this Plan.

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

Performance Element 5.1.4: Enhance national and international communication and collaboration concerning land ice state and processes.

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 space and time scales relevant to the missions of the participating agencies. Accomplishing these aims will require linkages with other parts of this Plan.

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.

Lead Agency: NSF
Supporting Agencies: NASA, DOE

Performance Element 5.2.2: Develop data sets to be used as boundary and forcing functions for ice sheet and glacier models.

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

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, 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, USGS

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

Authors: Andrew Balser (USACE), Benjamin Jones (USGS), April Melvin (AAAS-EPA)

Permafrost evolution, degradation, and properties influence terrestrial and aquatic ecosystems in Arctic and boreal regions (Bowden et al. 2012;[18] Hinzman et al. 2005; Shur and Jorgenson 2007), impacts infrastructure and economies (Walker and Peirce 2015; Larsen et al. 2008), affects human health (Arctic Climate Impact Assessment 2004), and alters global climate via the permafrost carbon feedback (Hugelius et al. 2014; 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 ~24% 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%), discontinuous (50-90%), sporadic discontinuous (10-50%), and isolated discontinuous (< 10%). 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 which 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). 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.

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[18] Paper presented at Tenth International Conference on Permafrost

The extent and dynamics of permafrost and permafrost-related landscape features remain poorly mapped and modelled at sufficient resolution for predicting 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; 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, estimate the spatial distribution of permafrost degradation modes (Balser and Jones 2015; Olefeldt 2015; Jones et al. 2015), and assess the vulnerability of permafrost carbon to quantify potential carbon release to the atmosphere.

Meeting this Goal will require strategic and diligently executed cooperation among Federal agencies with complementary capabilities, programs, and expertise. No single agency can accomplish the task alone. 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 Study of Environmental Arctic Change (SEARCH) Permafrost Carbon Network and Permafrost Action Team) 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 only partially understood. Warmer air temperatures are increasing permafrost temperature and thaw in many areas, changing hydrology, and influencing vegetation composition. 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, to improve understanding of the ground thermal regime of shallow and deep permafrost and its relationship with terrain properties.

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

Performance Element 6.1.2: Conduct field-based studies that examine and quantify relationships among surface topography, vegetation composition, hydrology and geophysical processes in permafrost soils to feed directly into models, decision support tools, and predictive analyses.

Lead Agencies: DOE, DOD (USACE), DOT (OST-R)
Supporting Agencies: DOI (NPS, USGS), NSF

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

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

Performance Element 6.1.5: Sustain the SEARCH Permafrost Action Team Network 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: DOI (USGS, FWS, BLM, NPS), DOE, NASA, NOAA, DOD (USACE)

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: Continue field-based research and monitoring necessary to improve understanding of the key processes controlling soil carbon cycling at northern latitudes and potential carbon release to the atmosphere.

Lead Agencies: NSF, DOI (USGS)

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

Performance Element 6.2.2: Sustain synthesis research conducted by the SEARCH Permafrost Carbon Network to improve scaling methods for estimating CO_2 and CH_4 emissions from the permafrost region, and link multi-agency investments in soil C research culminating in synthesis publications.

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

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: NASA, DOD (USACE), DOI (USGS)

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 the downstream effects of these events on microbial processes and carbon fluxes.

Lead Agencies: DOI (USGS), DOD (USACE)

Performance Element 6.2.5: Better understand the rate of subsea permafrost degradation and its role in 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), NSF, NOAA

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, 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, in order to benchmark the models. Improved predictive accuracy and understanding of permafrost/ecosystem process dynamics will directly enhance the ability to predict global climate 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 linking key terrestrial ecosystem processes and permafrost properties within models.

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

Performance Element 6.3.2: Carry out research on the processes responsible for changes to key disturbance regimes, including fire, thermokarst, and landscape changes caused by warming permafrost.

Lead Agencies: DOI (USGS, FWS), DOT (OST-R)
Supporting Agencies: NASA, DOI (BLM, NPS), DOD (USACE), NSF, USDA (USFS)

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

Lead Agencies: NASA, DOI (USGS, FWS, BLM)
Supporting Agencies: NSF, DOD (USACE), DOE, DOI (NPS), DOT (OST-R)

Performance Element 6.3.4: Coordinate activities directed at improving and integrating models of ecosystem processes at various scales, since permafrost dynamics are integral to these processes and vice-versa. Continue development of robust modeling tools and approaches. Organize and host workshop(s) to enable this activity across agencies engaged in data development, with attention to data congruity and scalability.

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

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 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 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 Agencies: DOI (BLM), DOT (OST-R)
Supporting Agencies: EPA, DHHS, Denali Commission, NIH, BIA, DOD (USACE, OSD)

Performance Element 6.4.2: Survey local communities and regional agencies involved with maintaining infrastructure and monitoring health on the impacts of warming and thawing of permafrost. Integrate these responses within a document characterizing and summarizing overall impacts from warming and thawing permafrost.

Lead Agencies: Denali Commission, DOD (OSD)
Supporting Agencies: DOT (OST-R), EPA, HHS, NIH, DOI (BLM, USGS), NOAA, DOD (USACE)

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

Authors: Eric Kasischke (NASA), John G. Dennis (NPS), Rachel Loehman (USGS), Diane McKnight (NSF), Jason J. Taylor (BLM Alaska)

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; 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. This 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, NPS, Bureau of Indian Affairs), U.S. Department of Agriculture bureaus (U.S. Forest Service, Natural Resources Conservation Service), the National Science Foundation (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, 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, NOAA's Alaska Center for Climate Assessment and Policy, 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 this 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 the observations, monitoring and conducting 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 the field-based research and monitoring needed to improve understanding of important ecosystem processes and feedbacks, including their responses to environmental changes.

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

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

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

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.

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

Performance Element 7.2.3: Incorporate scientific observations and the perspectives of IK and LEK 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 Agencies: DOI (USGS, FWS)
Supporting Agencies: DOI (BIA, BLM, NPS), NASA

Research Objective 7.3. Evaluate how changes in fire activity are impacting rural and urban communities, and 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.

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, USGS, NPS, FWS), NASA, NSF, USDA (USFS)

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, USGS, NPS, FWS), NSF, USDA (USFS)

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 and Natural and Built Environments

Authors: Rebecca Anderson (USGS), Amy Holman (NOAA), Simon Stephenson (NSF)

Research in Arctic coastal areas is complex and cross-cutting. Coastal areas are at the nexus of marine, terrestrial, and freshwater systems. They are home to the majority of Arctic human communities. They are at the forefront of climate change impacts such as flooding and coastal erosion, including some of the highest shoreline erosion rates in the nation with most of the northern coast retreating at rates of more than 1m per year (Gibbs and Richmond 2015). Many issues unique to the Arctic coastal zone are related to culture, food security, safety, infrastructure, biodiversity, and physical and biology processes. Researching the interconnections between people and natural and built environments of coastal areas is necessary to provide critical knowledge for navigating important decisions and informing policy regarding this distinctive geography. As a research topic, this is a rich area at the confluence of social, engineering, and natural science. Focusing research in Arctic coastal areas is helpful in moving national and local policy issues (*Well-being, Stewardship, Security)*.

Because issues in the Arctic involve many agency missions and mandates, it is necessary to take a multi-agency approach. Coordination of work by multiple groups is already taking place from local to international scales, and this goal builds on and strengthens that work. Under the U.S. Chairmanship of the Arctic Council and Arctic Executive Steering Committee Community Resilience Working Group, the Federal government has been engaged and working with multiple partners, including 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 to facilitate relocation of villages due to coastal erosion. Monitoring and modeling related to phenology and biodiversity will strengthen the work of state-federal partnerships such as the North Slope Science Initiative (NSSI) when working on scenarios to help identify future research and monitoring needs. The Alaska Climate Change Executive Roundtable (ACCER), which regularly discusses the role of science in understanding the ecological impacts of climate changes to the built environment, will benefit from research into physical coastal processes and enhanced observational data. Additionally, Landscape Conservation Cooperatives (LCCs) in Arctic coastal areas are actively engaging communities in research by convening coastal community workshops to learn about issues that are important on their landscapes and supporting community-based monitoring.

All steps of research —developing priorities and deliverables, designing projects, conducting research, disseminating results, and collaborating on deliverables—benefit from engagement with community members. Collaboration and engagement enable meaningful research among community members, Indigenous Knowledge (IK) and Local Ecological Knowledge (LEK) holders, and interagency researchers. Equally important is the process of sharing research results with communities in a format and delivery method that is commensurate with the needs and wants of the community itself.

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

***Rationale*:** Research is needed to inform strategies necessary for coastal communities to adapt to environmental, social, and economic changes in the coming years and decades. The majority of human habitation in the U.S. Arctic is in coastal areas where resources are available throughout the seasons, and it is important to plan and provide research findings on the sustainable economic development of coastal areas in a time of rapid change. When engaging in research in Arctic coastal areas, it is informative, productive, and respectful to work with community members, IK holders, and LEK holders, throughout the project, 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 participate in research about the places they live. Additionally, due to rapidly changing climate, physical, and biotic systems in Arctic coastal areas, it is important to document cultural artifacts and create tools to assist with modeling for planning, protect in-place strategies, and emergency response.

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

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

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

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)

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

Lead Agencies: DOI (NPS, BLM)

Performance Element 8.1.5: Advance the understanding of storm surge and saline inundation impacts on infrastructure and human safety. Multiagency partners include the State of 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 increased 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 CAFF Coastal Biodiversity Monitoring Programme Coastal Expert Monitoring Group* and research under the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative.

Lead Agencies: DOI (BOEM, USGS), NOAA
Supporting Agencies: DOI (BLM, NPS, FWS), 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 Bayesian network models of Arctic coastal organisms, including research under the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative.

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. Leverage research under initiatives and programs such as the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative, OneHealth, the Distributed Biological Observatory (DBO) network, the Arctic Marine Biodiversity Observing Network (ABMON), and Aerial Surveys of Arctic Marine Mammals (ASAMM) work.

Lead Agencies: DOI (USGS), NOAA, HHS
Supporting Agencies: DOI (BOEM, FWS), 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 and the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative.

Lead Agencies: DOI (FWS, USGS)
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. This includes the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative and a Western Alaska LCC-funded project on subsistence berry availability.

Lead Agencies: DOI (FWS, USGS)

Research Objective 8.3. Advance knowledge on 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 a loss of property and habitat—threatening the existence of coastal communities in 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: Further the understanding of coastal erosion and deposition, including related geomorphic changes due to permafrost degradation, reduced sea ice, storm surge, and increased wave action. This includes work by the USGS Coastal and Marine Geology Program, USGS Alaska Science Center, U.S. Army Corps of Engineers, and others.

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

Performance Element 8.3.2: Further the understanding of coastal freshwater hydrologic changes in rivers, lakes, snow, and permafrost through the USGS *Changing Arctic Ecosystems FY2015-2019* research initiative and USDA NRCS SNOTEL and SCAN soil moisture and temperature site monitoring.

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

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

***Rationale*:** Environmental intelligence on past conditions, current trends, and future projections are imperative for supporting the decisions community, state, and federal governments may need to make. It is extremely important that decision makers, from the local to international level, have the observations and baseline data needed to be supported and informed. To do this, it is necessary to ensure that accurate observations, mapping, and charting data are available for modeling and analysis across the entire coastal area. To support data collection, new sensors and technologies are needed to work year-round in Arctic coastal conditions and geographies.

Performance Element 8.4.1: Update baseline mapping and charting to enable research and predictive capabilities across the coastal interface. This includes additional charting in Arctic waters, updating baseline elevation and hydrography data in coastal areas, and updating targeted high resolution elevation data and repeated coverage. Multiagency partners include ACCER, Alaska Geospatial Council, and Arctic-related LCCs.

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

Performance Element 8.4.2: Update the *National Spatial Reference System* in the Arctic to enable research and prediction across the coastal interface to support research and predictive capabilities.

Lead Agency: NOAA

Performance Element 8.4.3: Develop new sensor technologies and data collection and application methods specific to understanding and characterizing relationships within coastal systems across all seasons. This element includes new oblique view applications using iGage by NOAA.

Lead Agency: NOAA

Performance Element 8.4.4: Produce modeled tidal predictions for the U.S. Arctic. Involve multiagency partners 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

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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 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 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.

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 DOI sponsor many Alaska-based programs directly concerned with research for stakeholder engagement and decision support, such as the Alaska Center for Climate Assessment and Policy (ACCAP), AOOS and FWS's Landscape Conservation Cooperatives (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 with valuable Arctic data products. While these efforts in the Arctic provide a solid foundation of knowledge and expertise, this 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, 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, Artic modeling can benefit from global and regional improvements to things like model resolution, as well as from comparative assessments among models (Research Objective 9.3). Arctic data stewardship, sharing and access is evolving from systems of the past 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 towards 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).

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 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 towards a system of observations. The U.S. AON should 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, and atmospheric monitoring facilities, these systems can form the foundation of an integrated pan-Arctic observing network.

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

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

Performance Element 9.1.2: Sustain multi-agency Research Coordination Networks to advance observational science and promote broad synthesis within thematic research communities by utilizing a nested observing framework include innovative and autonomous observing technologies suited to high latitude operations and community based monitoring.

Lead Agency: NSF
Supporting Agencies: NOAA, 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 in which the various components interact to affect one another. 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 climate through cryosphere impacts on Arctic, 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 in support of understanding connections between the Arctic and mid-latitude weather patterns and vice-versa.

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

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

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

Performance Element 9.2.3: Enhance understanding of processes, 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, radiative exchanges of energy throughout the system, etc.

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

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 our 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 our understanding of how well climate models perform, 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

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, NSF, NASA
Supporting Agency: DOE

Performance Element 9.3.3: Foster interactions between the Arctic Testbed and Environmental Modeling Center's High-Resolution Rapid Refresh 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: NASA, NOAA
Supporting Agencies: NSF, DOE, DOD (ONR)

Performance Element 9.3.6: Coordinate and support the Ice Sheet Model Intercomparison Project (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 our understanding of the cryosphere in a changing climate.

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

Research Objective 9.4. Enhance 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, and more. These centers 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. 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 IASC-SAON Arctic Data Committee in partnership 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 the capabilities, agencies would benefit from a shared vision for how data centers and tools could move toward greater interoperability. Such efforts will enable the toolkits and efforts on the front line of decision support such as the Climate Resilience Toolkit and the Arctic Domain Awareness Center's Arctic Information Fusion Capability.

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: NSF, NASA

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 and Alaska Data Integration Working Group (ADIWG).

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

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 and the Climate Resilience Tool Kit.

Lead Agencies: DOI, NASA, NOAA, NSF

Performance Element 9.4.4: Develop the DHS Arctic Domain Awareness Center's Arctic Information Fusion Capability (AIFC) to advance agile decision support for United States Coast Guard and other Arctic operators.

Lead Agency: DHS
Supporting Agencies: NOAA, NASA

Research Objective 9.5. Advance research, tools and strategies to improve the accessibility and usability 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. This collaboration supports a co-production of new knowledge that is clearly relevant and easily accessible for stakeholders. Many Federally-funded, and largely Alaska-based, organizations include sponsorships to convene regional forums to advance dialog and knowledge development. These forums draw together research communities and stakeholders to support decision-making; foci are often issue-specific (e.g., ocean acidification, integrated water level observations, community based monitoring) or geographic based (e.g., western Alaska, North Slope). The interagency platform can serve to enhance coordination of existing capabilities around issue-specific foci and geographic areas of broad concern.

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

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

Performance Element 9.5.2: Advance policy-relevant science communication through efforts like the annual *Arctic Report Card*[19] and SEARCH.

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

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[19] 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
Department of Agriculture
Department of Commerce
Department of Defense
Department of Energy
Department of Health and Human Services
Department of Homeland Security
Department of 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
U.S. Arctic Research Commission

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Abbreviations

AAAS	American Association for the Advancement of Science
AAPC	Alaska Arctic Policy Commission
ABMON	Arctic Marine Biodiversity Observing Network
ABoVE	Arctic-Boreal Vulnerability Experiment
ACCAP	Alaska Center for Climate Assessment and Policy
ACCER	Alaska Climate Change Executive Roundtable
ACEs	Adverse Childhood Experiences
ACF	Administration of Children and Families
ACLIM	Alaska Climate change Integrated Modeling project
ADEC	Alaska Department of Environmental Conservation
ADWIG	Alaska Data Integration Working Group
AEA	Alaska Energy Authority
AERONET	Aerosol Robotic Network
AESC	Arctic Executive Steering Committee
AFSC	Alaska Fire Consortium or Alaska Fisheries Center
AHRQ	Agency for Healthcare Research and Quality
AIFC	Arctic Information Fusion Capability
ALCC	Arctic Landscape Conservation Cooperative
AMAP	Arctic Monitoring and Assessment Program
AMOS	Arctic Mobile Observing System
AMSR2	Advanced Microwave Scanning Radiometer 2
ANTHC	Alaska Native Tribal Health Consortium
AON	Arctic Observing Network
AOOS	Alaska Ocean Observing System
Arctic-FROST	Arctic Frontiers of Sustainability
ARM	Atmospheric Radiation Measurement
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
CBRAT	Coastal Biodiversity Risk Analysis Tool
CCHRC	Cold Climate Housing Research Center
CDC	Centers for Disease Control
CLIVAR	Climate Variability and Predictability
CMIP	Coupled Model Intercomparison Project
CRREL	Cold Regions Research and Engineering Laboratory
DBO	Distributed Biological Observatory
DHHS	Department of Health and Human Services
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOJ	Department of Justice
DOS	Department of State
DOT	Department of Transportation
EDA	Economic Development Administration
EPA	Environmental Protection Agency
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
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
IHS	Indian Health Services
IK	Indigenous Knowledge
I-LEAD	Initiative for Leadership, Empowerment, and Development
ISMIP6	Ice Sheet Model Intercomparison for CMIP6
ISRO	Indian Space Research Organization
LC	Library of Congress
LCCs	Landscape Conservation Cooperative
LEK	Local Ecological Knowledge
LEO	Local Environmental Observer
LMEs	Large Marine Ecosystems
MAAT	Mean Annual Air Temperature
MMC	Marine Mammal Commission
MOM	Alaska Native Maternal Organics Monitoring Study
MOSAiC	Multi-disciplinary Drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
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	The 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 Disparities
NIOSH	National Institute for Occupational Safety and Health
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
NSB	National Baseline Study
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
OJJDP	Office of Juvenile Justice and Delinquency Prevention
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OSH	Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
OST-R	Office of the Assistant Secretary for Research and Technology
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
UAS	Unpiloted Arial Systems
US AON	US Arctic Observing Network
USACE	US Army Corps of Engineers
USARC	US Arctic Research Commission
USCG	United States Coast Guard
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite
VPSO	Village Public Safety Officers
WASH	Arctic Water, Sanitation and Hygiene
WIHAH	Water Innovations for Healthy Arctic Homes