IARPC

Interagency Arctic Research Policy Committee

Report to Congress on the Arctic Research Plan 2017-2021

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Cover Image: Science Technician Marci Beitch launches a radiosonde in high winds as part of the National Science Foundation-sponsored program, Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit (ICECAPS). Credit: August Allen, Polar Field Services

The National Science and Technology Council (NSTC)

February 28, 2022

Dear Members of Congress and the Arctic Research Community,

We are pleased to forward the Interagency Arctic Research Policy Committee (IARPC) 2021 Biennial Report. This report, called for in the Arctic Research Policy Act of 1984 (15 U.S.C. §4108), presents progress on implementation of the recently concluded 2017-2021 Arctic Research Plan, highlighting major accomplishments of the Federal agencies and broader research community completed under the plan.

The Biden Administration has identified tackling the climate change crisis as a key priority, and, in the Arctic, climate change is transforming the region at an alarming pace and scale. Warming temperatures, melting ice, and broad-scale ecosystem transitions have tremendous implications for the well-being of Arctic residents and the nation, presenting an urgent need for well-coordinated, cooperative research.

This report reflects the outcomes of that cooperation, highlighting areas in which IARPC has helped bring together Federal agencies and the Arctic research community to advance our understanding of the Arctic system for the benefit of those communities most affected by climate change. As you will see in this report, much of the work IARPC has accomplished has been facilitated through partnerships. The numerous projects detailed on the following pages represent only a fraction of IARPC's achievements over the last five years.

The work completed under the 2017-2021 plan sets the stage for continued cooperation and knowledge generation to help tackle the climate crisis in the Arctic Research Plan 2022-2026. Released in December 2021, the plan presents a bold new holistic vision for the future of Federally funded research in the Arctic. We appreciate your continued support as we work together to address some of the most pressing and challenging research questions of our time.

Sincerely,

Jane Lubchenco

The Honorable Jane Lubchenco, Ph.D.
Deputy Director for Climate and Environment
Office of Science and Technology Policy
Executive Office of the President

Panchanathan

The Honorable Sethuraman Panchanathan, Ph.D.
Director, National Science Foundation

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development enterprise. A primary objective of the NSTC is to ensure science and technology policy decisions and programs are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across Federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at www.whitehouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of Federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the Federal Government. More information is available at www.whitehouse.gov/ostp.

About the Interagency Arctic Research Policy Committee

The Arctic Research and Policy Act of 1984 (ARPA), Public Law 98-373, July 31, 1984, as amended by Public Law 101-609, November 16, 1990, Public Law 103-199, December 17, 1993, and Public Law 109-241, July 11, 2006, provides for a comprehensive national policy dealing with national research needs and objectives in the Arctic. The ARPA establishes an Arctic Research Commission (USARC) and an Interagency Arctic Research Policy Committee (IARPC) to help implement the Act. Since its inception, IARPC activities have been coordinated by the National Science Foundation (NSF), with the Director of the NSF as chair. A Presidential Memorandum issued on July 22, 2010, made the NSTC responsible for IARPC, with the Director of the NSF remaining as chair of the committee.

About This Document

This End-of-Plan Report compiles and highlights major achievements of Federal agencies and IARPC Collaboration Teams to demonstrate how IARPC has improved understanding of the Arctic within the period of the 2017-2021 Arctic Research Plan. Legislation mandates IARPC produce a biennial report of accomplishments to Congress; the End-of-Plan Report serves this purpose while also serving as a tool to communicate the most important findings of IARPC-supported research. This report is published by OSTP.

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Kelley Uhlig looks through Van Veen grab (an ocean sediment sample) specimens in the lab aboard the USCGC Healy icebreaker in the Beaufort Sea. Credit: Lindsey Leigh Graham

CH.1 Tackling Holistic Challenges Through Collaborations

CH.2 Improving Observations of the Arctic System

Acronyms

ARM
Atmospheric Radiation Measurement user facility (DOE)

ARP
Arctic Research Plan

AUVs
Autonomous underwater vehicles

BOEM
Bureau of Ocean Energy Management

CHAOZ
Chukchi Arctic Oceanographic and Zooplankton Study

CICE
Los Alamos Sea Ice Model, better known as Community Ice Code

CMIP6
6th Model Intercomparison Project

COMBLE
Cold-Air Outbreaks In the Marine Boundary Layer Experiment

DBO
Distributed Biological Observatory

DOE
U.S. Department of Energy

DOD
U.S. Department of Defense

DOI
U.S. Department of the Interior

E3SM
Energy Exascale Earth System Model

GRACE
Gravity Recovery and Climate Experiment

GRACE-FO
Gravity Recovery and Climate Experiment–Follow On

HAB
Harmful Algal Bloom

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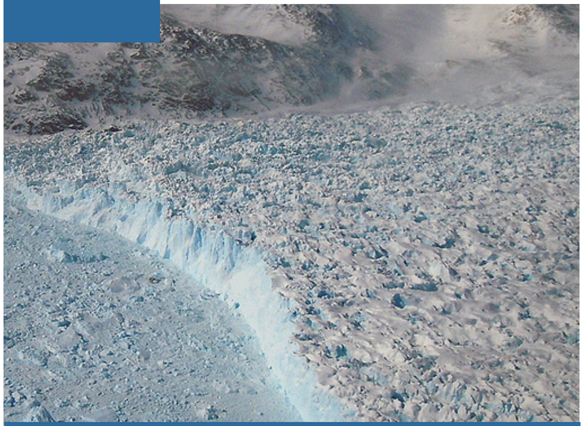
ICESat
Ice, Cloud and Land Elevation Satellite

ICESat2
Ice, Cloud, and Land Elevation Satellite–2

InteRFACE
Interdisciplinary Research For Arctic Coastal Environments project

CH.3 Modeling and Projecting the Future Arctic



CH.4 Applying Research to Human Needs

MEaSUREs
Making Earth System Data Records for Use in Research Environments

MOM6
Modular Ocean Model

MOSAiC
Multidisciplinary drifting Observatory for the Study of Arctic Climate

NASA
National Aeronautics and Space Administration

NGEE Arctic
Next Generation Ecosystems Experiment

NOAA
National Oceanic and Atmospheric Administration

NPS
National Park Service

NSF
National Science Foundation

OCS
Outer Continental Shelf

SIPN
Sea Ice Prediction Network

SIWO
Sea Ice Walrus Outlook

SAON
Sustained Arctic Observing Network

SOAR
The Synthesis of Arctic Research

SODA
Stratified Ocean Dynamics of the Arctic

STEM
Science, technology, engineering, and mathematics

UAF
University of Alaska Fairbanks

USARC
U.S. Arctic Research Commission

USFWS
U.S. Fish and Wildlife Service

USGS
U.S. Geological Survey

Executive Summary

Across the Arctic, warming temperatures have induced rapid environmental change, affecting Arctic communities, ecosystems, and global human activities. The United States, an Arctic nation, is thus invested in better understanding such changes and their impact on communities' well-being, environmental stewardship, national security, and fundamental science.

Established by an act of Congress in 1984, the Interagency Arctic Research Policy Committee (IARPC) works to set a coordinated agenda for Federally funded Arctic research in the United States. Every five years, IARPC produces a research plan that details the research areas where interagency coordination can more effectively advance the state of knowledge about the Arctic system. IARPC also produces biennial reports to Congress highlighting the progress made toward implementing the most recent Arctic Research Plan.

This report serves as the 2021 Progress Report to Congress and coincides with the conclusion of the 2017-2021 Arctic Research Plan. It provides an overview of some of IARPC's most relevant achievements and accomplishments over the duration of the plan. We solicited contributions from both IARPC member agencies and the collaboration teams, groups of IARPC members working toward a goal defined in the Arctic Research Plan.

IARPC serves the Arctic research community foremost as a venue for collaborations to take hold. Using the unique IARPC Collaborations platform, member agencies, collaboration teams, and non-Federal parties engage with each other to build relationships necessary for successful science.

In Chapter 1, this report demonstrates the value of IARPC Collaborations as a tool for originating and coordinating Arctic research in the United States. Among the fundamental aspects of research are observational and experimental study of the Arctic system, which IARPC member agencies and teams have deeply engaged in over the last five years.

Agencies and collaboration teams of IARPC are also deeply engaged in human-centered research, as detailed in Chapter 4. This work indicates the advances in Alaska community health, infrastructure development, and environmental safety, emphasizing collaboration with Indigenous Peoples and co-production of knowledge, and the development of resilient Arctic communities.

While the body of work highlighted in this report is substantial, it captures only a fraction of the effort IARPC member agencies and collaboration teams contributed over the last five years. Yet, much work remains to be done in understanding the Arctic system. As IARPC releases its next five-year plan, the progress achieved here serves as a solid foundation for these continued efforts.

IARPC's Role in Arctic Research

The icebreaker *R/V Polarstern* was frozen into the ice for a year during the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. Researchers had to be resourceful in the remote central Arctic, where cracks in the ice floe are common. Here they put down a sled to use as a footbridge for safe crossing. Credit: U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility, Matthew Shupe, University of Colorado, Boulder

The Arctic affects life both in Alaska and across the United States. Consequently, the alarming pace and scale of change within the Arctic presents an urgent need for well-coordinated, cooperative Arctic research.

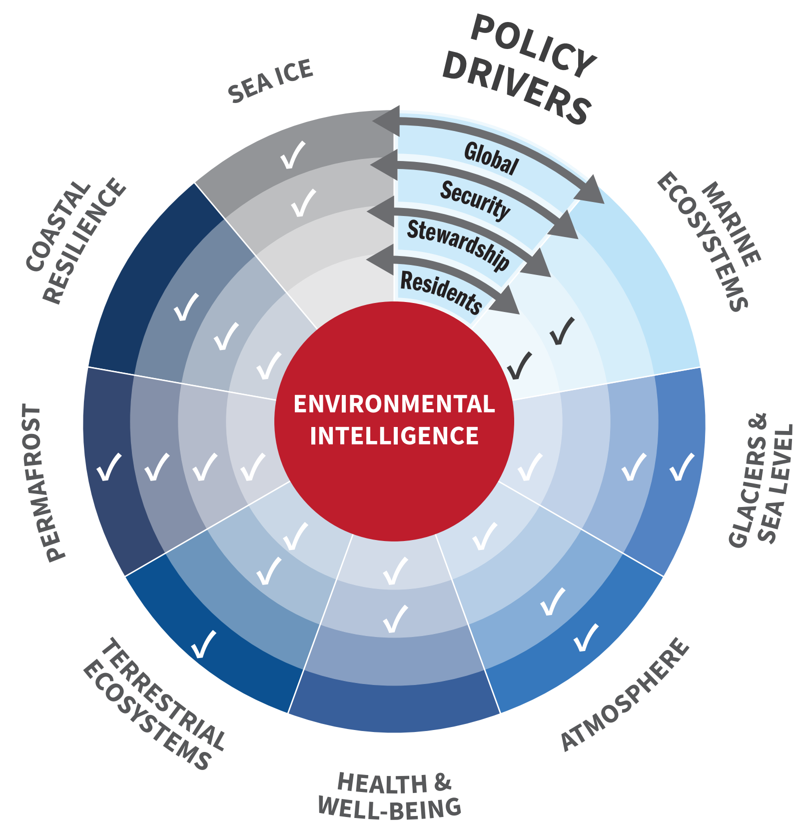
Situated within the National Science and Technology Council (NSTC), IARPC aims to address this need by enhancing scientific research and monitoring of local, regional, and global environmental issues in the Arctic. IARPC exercises this role through cooperation across 16 Federal agencies, departments, and offices as well as by collaboration with outside partners through its implementation structure, IARPC Collaborations, which is coordinated by five-year Arctic Research Plans.

The 2017-2021 Arctic Research Plan presented a common research agenda that identifies research areas where agency strengths can be leveraged to make Federal Arctic research more effective[1]. In addition, the plan adheres to four critical policy drivers that reflect vital areas where the U.S. Arctic research enterprise supports U.S. policy from community to global scales. They reflect the collective priorities of IARPC Federal agencies and are derived from the major U.S. policy documents of the past 50 years. Policy drivers include:

1. Enhance the **well-being** of Arctic residents;
2. Advance **stewardship** of the Arctic environment;
3. Strengthen national and regional **security**; and
4. Improve **understanding** of the Arctic as a component of planet Earth.

In addition to the four policy drivers, the plan describes nine research goals—broad topics identified by IARPC as points where the interagency approach can accelerate progress. These goals build upon the work of the previous Arctic Research Plan (2013-2017) and integrate a greater understanding of the components of the Arctic system to address the increasing complexity of research and informed decision-making. Aligned to the nine collaboration teams, these goals are:

1. Enhance understanding of **health determinants** and improve the **well-being** of Arctic residents;
2. Advance process and system understanding of the changing Arctic **atmospheric composition and dynamics** and the resulting changes to surface energy budgets;
3. Enhance understanding and improve predictions of the changing Arctic **sea ice cover**;
4. Increase understanding of the structure and function of Arctic **marine ecosystems** and their role in the climate system to advance predictive capabilities;
5. Understand and project the mass balance of **glaciers, ice caps, and the Greenland Ice Sheet**—and their consequences for sea-level rise;
6. Advance understanding of processes controlling **permafrost** dynamics and the impacts on ecosystems, infrastructure, and climate feedbacks;
7. Advance an integrated, landscape-scale understanding of Arctic **terrestrial and freshwater ecosystems** and the potential for future change;
8. Strengthen **coastal community resilience** and advance stewardship of coastal natural and cultural resources by engaging in research related to the interconnections of people and natural and built environments; and
9. Enhance frameworks for **environmental intelligence** gathering, interpretation, and application toward decision support.



The 2017-2021 Arctic Research Plan set nine research goals, indicated by the vertical wedges of different colors, which align to the four policy drivers. Check marks indicate to which policy drivers each research goal is best aligned.

This report highlights salient accomplishments and achievements resulting from the 2017-2021 Arctic Research Plan. In the process of developing this report, we asked member agencies and collaboration teams to submit short summaries of their most notable accomplishments of the last five years. In all, more than 60 pages of submissions were received. This report includes just a fraction of these responses, which were themselves a subset of IARPC's total work over the last five years.

These projects represent collaborations across Federal agencies and academic institutions, Arctic communities, and other non-Federal partners to advance the state of knowledge of the Arctic system. A primary challenge in presenting these accomplishments is to accurately reflect the often unseen nature of collaboration and co-production early in the research lifecycle—that IARPC promotes and characterizes the unique, holistic nature of IARPC research products. To this end, this report acknowledges contributions from all agencies and collaborative teams that could not fit within the confines of this report. Summary statements for all performance elements in the plan are being prepared by agencies and collaboration teams and will be available on the IARPC Collaborations website.

Beginning with a focus on the IARPC Collaborations web platform and resulting coordination, Chapter 1 of this report highlights how member agencies and collaboration teams have come together to build a new understanding of the Arctic system. Chapter 2 reports on the improved observations and experimental research that has helped quantify atmospheric systems, the changing cryosphere, and changing ecosystems. Chapter 3 demonstrates modeling advancements, including how such data are translated to improve existing models and projects and build new modeling tools to understand the Arctic and global systems. Chapter 4 highlights human-centered projects emphasizing community health, infrastructure, and environmental safety.

IARPC BY THE NUMBERS

16

Federal Agencies and Offices Working Together

12

Collaboration Teams Focusing on an Area of Study Supporting:

9

Research Goals

122

Performance Elements to Organize Collaboration Team Activities

10

Additional Self-Formed Teams Using the IARPC Collaborations Platform to Coordinate

CH.1 Tackling Holistic Challenges Through Collaborations

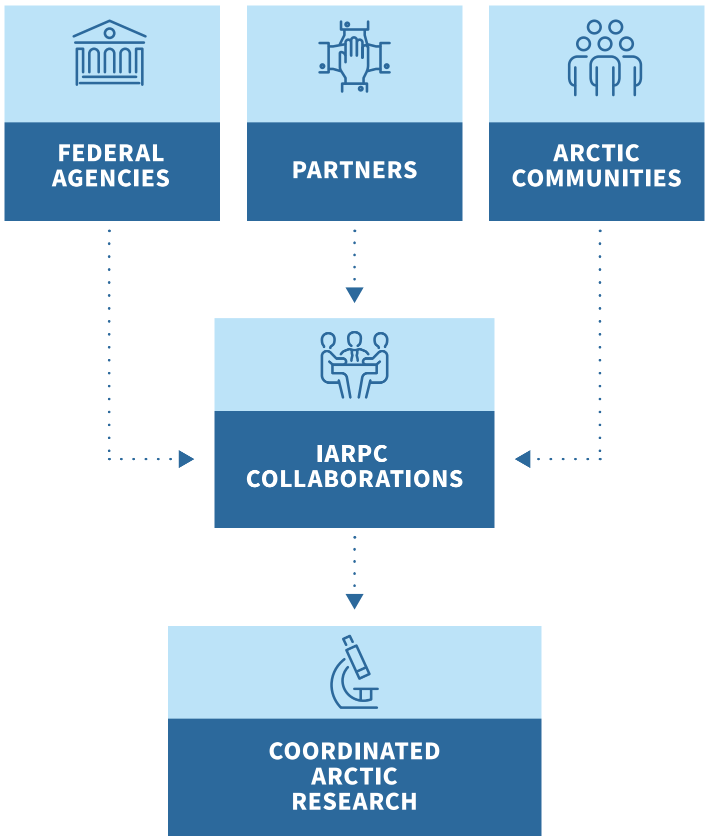
In 2016, a small team of subject-matter experts from BOEM's Alaska Outer Continental Shelf (OCS) Region and its Sterling, Virginia headquarters traveled around Alaska hosting a series of public meetings to get public input on a draft environmental impact statement prepared to analyze the potential environmental impacts of the 2017-2022 Proposed Five-Year Program. Credit: John Callahan/BOEM

Research is traditionally measured in easily quantified metrics: data produced, papers published, and dollars spent. However, the foundation of any tangible research product is open access to communication and collaboration across communities of practice that enable new ideas and partnerships to take hold that in turn can lead to societal benefits. Therefore, the best record of IARPC achievements is not just the research produced but the often-unseen processes that allowed the research to be conceived and executed.

Unique among Federal bodies, IARPC has built a community that allows easy communication and collaboration among agencies and non-Federal partners like academic researchers and Indigenous communities. In doing so, IARPC has broadened access to the entire scientific pipeline and built an infrastructure for better understanding the Arctic system.

IARPC Collaborations Platform

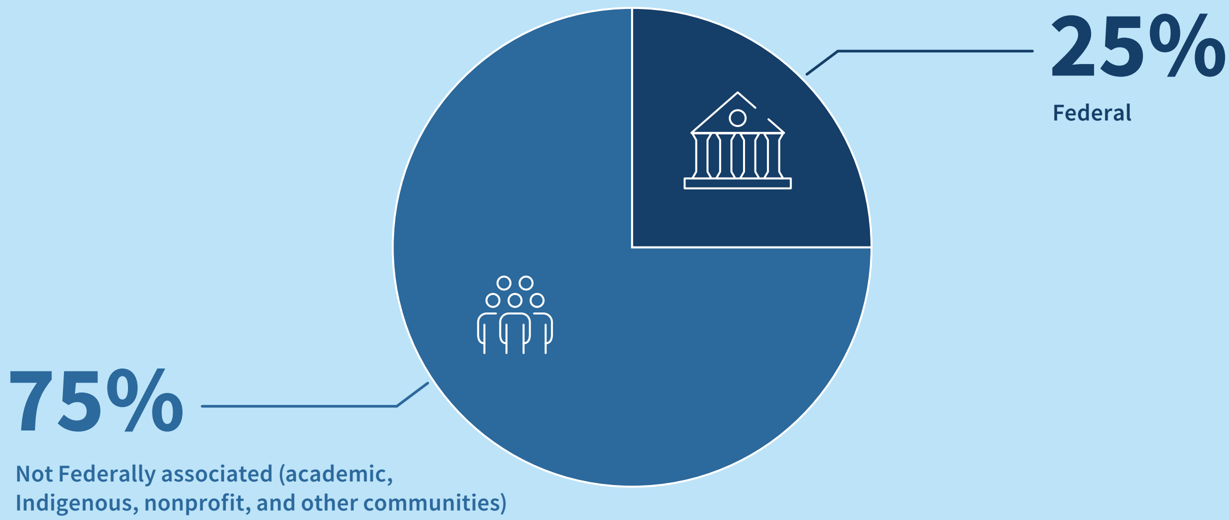
Established within the Arctic Research and Policy Act of 1984[2], as amended, IARPC and its sister agency, the U.S. Arctic Research Commission (USARC), have a unique mandate among interagency bodies to enable work between the Federal government and other organizations engaged in Arctic research. To fulfill this charge, IARPC established a novel platform, IARPC Collaborations, to build connections across the broader Arctic research community. The Collaborations platform connects Federal government researchers, non-Federal scientists, Indigenous Peoples, and stakeholders through a website featuring message boards, events, document sharing, and more.



A Diverse and Growing Community

Since its development in 2010 and throughout the 2017-2021 Arctic Research Plan, the Collaborations platform has supported an unprecedented degree of interagency communication, coordination, and collaboration that has advanced Arctic science. IARPC Collaborations has grown steadily since its inception, representing wide-reaching and active community engagement.

During the 2017-2021 Arctic Research Plan alone, membership in IARPC Collaborations grew by 200%. IARPC uniquely enables large-scale interactions across agencies as well as between agencies and non-Federal partners. Of the nearly 3,000 members of IARPC Collaborations, almost 75% are not Federally associated and instead represent academic, Indigenous, nonprofit, and other communities of practice.



Collaboration Teams for Changing Needs

A central feature of the IARPC Collaborations platform, nine collaboration teams—representing scientists, community members, Federal employees, and others—directly embody the holistic research questions identified as goals within the Arctic Research Plan. Formed in 2013, collaboration teams enhance the implementation of the Arctic Research Plan through research and community engagement and are open to anyone wishing to advance knowledge about the Arctic.

In addition, three sub-teams representing cross-team topics were included in the original plan under the Environmental Intelligence Collaboration Team.

The IARPC Collaborations platform has allowed these teams to grow throughout the Arctic Research Plan with easy documentation of progress amongst the members. In addition to the collaboration teams, 10 self-forming teams have arisen to expand the capabilities and scope of IARPC Collaborations and address topics that span multiple research goals.

These teams address questions rooted in a better understanding of the Arctic system that can also foster more robust and equitable community development, including diversity, equity, inclusion, STEM education, international cooperation, and support for early-career scientists. The organic nature of these teams demonstrates the uniquely adaptive value the Collaborations platform brings to IARPC agencies and members.

IARPC Collaboration Teams

IARPC is mandated for interagency coordination and collaboration with non-Federal science and research partners in the state of Alaska, academia, industry, Indigenous Peoples, and more. To do this, IARPC initiated nine Collaboration Teams whose joint activities advance the research goals outlined in the IARPC 5-year plan.

Collaboration Teams

- Atmosphere
- Coastal Resilience
- Environmental Intelligence
- Glaciers & Sea Level
- Health & Well-being
- Marine Ecosystems
- Permafrost
- Sea Ice
- Terrestrial Ecosystems

Sub-Teams

- Arctic Data
- Arctic Observing Systems
- Modeling

Self-Forming Teams

- Arctic Domain Awareness Center Network
- Arctic STEM Education Working Group
- Cold/High Anaerobic Digestion
- Diversity & Inclusion Working Group
- Early Career Forum
- International Cooperative Engagement Program for Polar Research (ICE-PPR)
- Physical Oceanography
- Polar Technology Community Forum
- Science Communication Forum
- U.S. Forum for the International Arctic Science Committee (IASC)

Relationships to Support Improved Research

A primary function of IARPC is to improve the Federal landscape for Arctic research by making the work more efficient and leveraging monetary investment for more significant research gain. In this role, IARPC Collaborations had brought together a variety of actors to better address the holistic nature of the Arctic system across agencies, cultures, and countries. As collaboration represents the backbone of IARPC's effort, the following examples illustrate how cooperation has helped shape the research community—providing insight into the foundation of projects later mentioned in this report.

Building Interagency Relationships

Within the last five years, IARPC has facilitated a multitude of interagency projects, many of which are detailed in the remainder of this report. Underlying the successful completion of these projects are the stories of interagency coordination under the umbrella of IARPC. These stories were enabled by individual relationships built through collaboration teams.

One such program, the Stratified Ocean Dynamics in the Arctic (SODA) project, grew from a single agency effort initiated by the Office of Naval Research (ONR) into SODA+, an interagency project involving the National Oceanic and Atmospheric Administration (NOAA), NASA, National Science Foundation (NSF), Bureau of Ocean Energy Management (BOEM), and United States Geological Survey (USGS).[3]

In 2020, IARPC managed interagency collaboration in the face of a novel challenge. As the COVID-19 pandemic shut down nearly all travel and threatened to derail scientific efforts in the Arctic, IARPC-led communication allowed for a rapid interagency response that resulted in pooled ship time, preserving critical time series like the Distributed Biological Observatory[4] and providing a platform for Indigenous Peoples organizations to post their COVID-19 plans.

Principles of Arctic Research

Building Relationships with Indigenous Peoples

An increased emphasis by IARPC on building improved relationships between non-Indigenous groups and Indigenous communities has led to better communication and alignment of research products to local needs. To support this emphasis, groundwork for new and ongoing projects actively seeks out Indigenous knowledge.* IARPC has added to its portfolio initiatives to bring more Indigenous Knowledge into the planning and conduct of IARPC's interdisciplinary work. Supported by NSF, IARPC released a new set of Principles for Conducting Research in the Arctic (2018), revised with more than 100 comments from academic researchers, Federal agency representatives, Indigenous representatives, and other people who live, work, and conduct research in the Arctic.

Additionally, IARPC has set the stage for improved science products by highlighting the complementary nature of Western and Indigenous knowledge systems. Listening to the input from the Alaska Eskimo Whaling Commission, Inuit Circumpolar Council, Kawerak, Inc., and Pew Charitable Trusts, for example, has led to fruitful conversations and laid the groundwork for new and ongoing projects that actively seek out Indigenous knowledge. Supported by NSF, IARPC has partnered with Federal government agencies and non-Indigenous academic researchers to bring more Indigenous Knowledge into its planning and conduct of IARPC's interdisciplinary collaboration teams.

The fall 2020 workshop to identify potential cross-cutting priority areas for the next Arctic Research Plan (2022-2026) included Indigenous participants who provided helpful insight to some Indigenous community concerns. Many of the responses during this workshop were included as areas of emphasis in the next plan. The NSF's multi-year Navigating the New Arctic (NNA) exemplifies a range of research projects with diverse goals that include

* 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. It has developed over millennia and is still developing in a living process, including knowledge acquired today and in the future, and it is passed on from generation to generation (Inuit Circumpolar Council, 2020).

Illustration of the MOSAiC expedition's Central Observatory, consisting of the main Ice Camp and R/V *Polarstern* anchored to the ice floe. Beyond surface and ice tethered installations, researchers used airborne, satellite, and under-ice instruments. Credit: Alfred Wegener Institute strengthening collaborations between scientists and Indigenous Knowledge holders.[5]

NSF also took several actions to support Indigenous individuals and organizations to become more engaged in NSF's funding process; to improve the relationship among the agency, NSF-funded Principal Investigators (PIs), and local and Indigenous peoples living in the Arctic; and to improve the ability of NSF-funded investigators to incorporate Indigenous Knowledge into their projects. Notable among these was partnering with University of Colorado Boulder, Alaska Pacific University, and University of Alaska Fairbanks to establish an NNA Community Office.

Finally, Federal IARPC agencies provided primary funding for the Local Environmental Observer (LEO) Network, founded in 2016 by the Alaska Native Tribal Health Consortium, uses community-based monitoring and Indigenous and local knowledge to strengthen reports of unusual animal behavior or environmental and weather events across the circumpolar north.[6]

While all these projects and initiatives improved connections with Indigenous communities, much work remains to develop full co-production and truly equal standing of Indigenous and non-Indigenous knowledge.

Building International Relationships

The last five years have seen growing international collaboration within the world of Arctic research, exemplified by the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), the largest Arctic expedition ever undertaken.[7] IARPC worked closely with other U.S. and international organizations to help coordinate U.S. efforts—the second-largest funding contribution to the international program. Many of the projects detailed in this report contributed to MOSAiC during the expedition. On land, IARPC and collaboration teams worked to contextualize and share results of the voyage.

The Data Collaboration team helped lay the groundwork for an international and national collaborative network consisting of a mix of U.S. Federal and non-Federal sectors, focused on advancing FAIR (Findable, Accessible, Interoperable,

International collaborations drive much of Arctic science. Here, the German research icebreaker Polarstern (foreground) and the U.S. Coast Guard cutter Healy meet at the North Pole as part of the international GEOTRACES research program.
Credit: Alfred-Wegener-Institute/Stefan Hendricks

Case Study

Innovative Partnerships Forged via IARPC Collaborations Allowed Study of Rapid Changes in Arctic Marine Ecosystems

The staff of the North Pacific Research Board (NPRB)[8], a non-Federal entity, found opportunities to forge new relationships via IARPC Collaborations to address complex changes in Arctic marine ecosystems. NPRB cooperated with BOEM, the ONR Marine Mammals & Biology Program, and the North Slope Borough/ Shell Baseline Studies Program to design and fund more than $18 million in multidisciplinary research. NOAA, NSF, UAF, and USFWS provided generous in-kind support. The innovative partnership included the perspectives of Federal agencies, a regional Alaska government entity, individual Alaska communities, and private industry.

The Arctic Integrated Ecosystem Research Program[9] linked observations of changes in ocean physics and chemistry to significant changes observed throughout the biological ecosystem, from plankton and marine invertebrates to fish, seabirds, and marine mammals. The program also involved Arctic community members who discussed food security in the context of environmental change and other drivers, including socioeconomics and policy.

and Reusable) principles for data management.

The U.S. Department of Defense developed a Memorandum of Understanding (MOU) with partner nations to improve defense and security capabilities in the Arctic. The International Cooperative Engagement Program for Polar Research (ICE-PPR) is the vehicle for this collaboration. International partners include:

- United States of America Department of Defense (USA DoD)
- The Department of National Defence of Canada (CAN DND)
- The Ministry of Defence of the Kingdom of Denmark (DEN MOD)
- The Ministry of Defence of the Republic of Finland (FIN MOD)
- The New Zealand Defence Force (NZDF)
- The Ministry of Defence of the Kingdom of Norway (NOR MOD)
- The Government of the Kingdom of Sweden (SWE)

These partners recognize the benefits to be obtained from standardization, rationalization, and interoperability of military equipment, which eliminates unnecessary duplication of work, encourages interoperability, and obtains the most efficient and cost-effective results through cooperation in Polar Research, Development, Test, and Evaluation projects.

Ultimately, the goal is to improve respective conventional defense and security capabilities through the application of emerging technology to satisfy common operational requirements. The underlying theme of this work is a shared desire for strong cooperative relationships that preserve safe, stable, and secure Polar regions. The MOU was signed in November 2019 and is effective for 25 years.

While IARPC helps coordinate U.S. engagement with international programs, the establishment of the Arctic Research Plan helps international Arctic programs and non-U.S. researchers better understand the priorities and processes of the U.S. Arctic research enterprise.

Biologists visit a marked shorebird next on the tundra in Alaska during the 2019 Arctic Bird Fest. Credit: Lisa Hupp, USFWS

CH.2 Improving Observations of the Arctic System

Denver Holt checks out a snowy owl chick to make sure that all of its limbs work in the correct way. Denver records all of his observations about every chick at every nest he visits. Barrow, Alaska. Credit: Elizabeth Eubanks (PolarTREC 2008), Courtesy of ARCUS

IARPC amplifies existing and developing Arctic observations, bringing together work from academic institutions, Federal agencies, the State of Alaska, Indigenous communities, other Arctic residents, and other partners.

Over the last five years, IARPC member agencies and collaboration teams worked together to improve observations of the Arctic, ranging from gathering fundamental data about the thawing and melting cryosphere to sophisticated surveys and measurements of changing terrestrial and marine ecosystems.

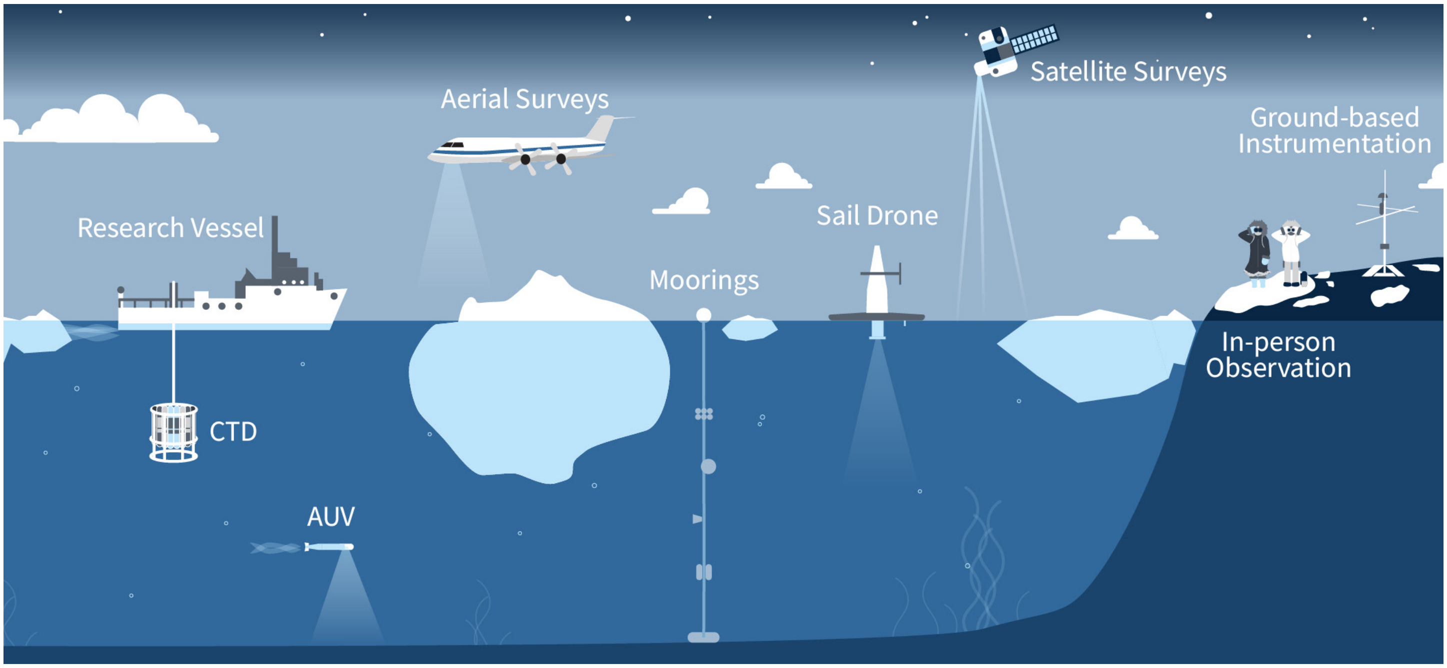
IARPC has helped identify synergies among observation projects and data sets by bringing these observations together into a multi-pronged investigation. IARPC teams have addressed policy drivers of the Arctic Research Plan—directly improving environmental stewardship and advancing understanding of global connections.

Monitoring Atmospheric-Oceanic Change

In addition to foundational observations of the changing system, IARPC teams and agencies analyzed significant climate events, transitions, and phenomena that represent a new Arctic characterized by warmer temperatures.

Observing Heatwaves and their Impacts

Abnormally high—both atmospheric and marine—characterized the Arctic system over the last five



IARPC member agencies and scientists employ technology to observe and quantify the Arctic environment. Within the marine environment, research vessels (far left) host instrumentation, including those deployed over the gunwale of the ship, such as sensors attached to a conductivity, temperature, depth (CTD) rosette. Within the water, autonomous underwater vehicles (AUVs) use remote sensing to capture data, for example, using multibeam surveys to capture seafloor bathymetry. Similar remote sensing is achieved from aerial surveys, uncrewed aerial vehicles (UAVs), and satellite surveys. Sail Drones provide surface-based marine surveys over long tracts, while moorings anchored to the seafloor can provide time-series observations of marine data in a single location. On land, ground-based instruments advance knowledge of permafrost, freshwater, land ice, and other terrestrial ecosystems, while Indigenous and Western observing systems are achieved with direct human surveys.

years. From over 30 climate stations across Alaska, the National Park Service (NPS) saw an abrupt increase in mean annual air temperature beginning in 2014, which persisted over the entire period of the plan.[10] In addition, marine heatwaves, which are expected to become increasingly common, were strong enough to override typical ecosystem drivers within the Gulf of Alaska.

Extreme heat altered the community structure of forage fish with impacts to multiple other species, such as seabirds and marine mammals. It also altered the rocky intertidal zone, shifting it from net autotrophic to heterotrophic, meaning the waters changed from overall oxygen-producing to oxygen-consuming, according to the Gulf Watch Alaska Long-Term Monitoring Program, a program with contributions from USGS, NOAA, NPS, USFWS, and non-Federal partners.[11]

Effects of Changing Ocean Stratification

Additional research sought to identify the long-term effects of warming and the resulting ice loss. The ONR-led SODA program was motivated by observed changes in the Bering and Chukchi seas during summer periods of open water. The project sought to understand how layered water masses affect how heat from the Pacific Ocean moves through the Arctic. The goal: to better understand ocean circulation and sea ice growth, especially in an era of reduced ice thickness and extent.

SODA grew into an interagency project with the help of IARPC. Initial results suggest stronger seasonality in sea ice cover may enhance energy exchange between the atmosphere and ocean.

The Complexities of Arctic Clouds

On land, the U.S. Department of Energy (DOE), through the Atmospheric Radiation Measurement (ARM) user facility[12], has provided critical measurements to understand changing Arctic atmospheric composition and dynamics and the changes to surface energy budgets (the accounting of energy in and out of the Earth's surface). Comprehensive measurement sites in northern Alaska (Utqiaġvik and Oliktok Point) and Greenland, as well as mobile deployments in collaboration with the international efforts of MOSAiC and the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE), contributed to the developing understanding of complex atmospheric processes, such as cloud formation and cover.

A visitor heads to ARM's radar wind profiler platform, which also hosts a sunphotometer, surface meteorology instrumentation and microwave radiometer profiler, at the ARM North Slope of Alaska (NSA) atmospheric observatory in Utqiaġvik, Alaska. Credit: U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility

Foundational Observations of the Changing Cryosphere

Climate change affects the cryosphere first, and in turn, causes cascading effects through the Arctic ecosystem. Observing and quantifying changes to the cryosphere is, therefore, one of the most fundamental aspects of Arctic

Glacial melt in Alaska. Credit: Neal Herbert/National Park Service

research, and it is a cross-cutting goal of the 2017-2021 Arctic Research Plan.

Remote sensing and satellite observations of sea ice, glaciers, and permafrost serve as a foundational way to quantify ice loss. These efforts are complemented by valuable air- and surface-based measurements. IARPC-member agencies and collaboration teams are deeply engaged in these continued observations.

Satellite Observations, Fundamental Data

Several IARPC member agencies and collaboration teams supported the continuation of existing satellite programs and the development of new observation platforms. For instance, Landsat 8, co-managed by NASA and USGS, continues the longest space-based satellite record of Earth's land in existence. It observes the pan-Arctic domain with thermal infrared image products that are used to study snow cover, ice flow and ice melt, snow and ice albedo (a measure of solar radiation reflection), melt ponds (pools of melted snow atop sea ice), supraglacial lakes (pools of melted freshwater on top of glaciers), glacier mass balance, primary productivity (photosynthesis) in the ocean, and open-water navigation.

The Glaciers and Sea Level collaboration Team worked with NASA's Earth Systematic Missions Program to develop, introduce, and use the Ice, Cloud and Land Elevation Satellite 2 (ICESat2) and the intermediary airborne program,[13] Operation IceBridge (OIB).[14] These efforts work together to produce multiple fundamental and broadly used data sets that quantify changes in Arctic landscapes and icescapes.

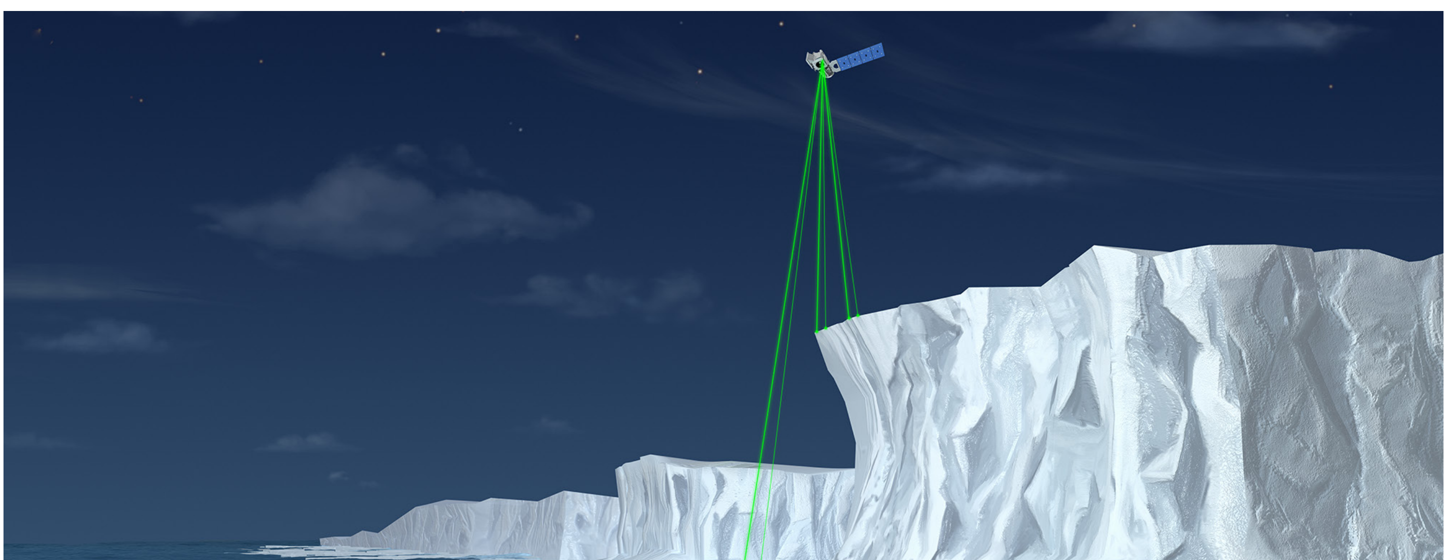
Launched in 2018, ICESat-2 added a powerful new instrument to observe the cryosphere, a photon-counting, multi-beam laser altimeter, which served as a successor to the original ICESat laser altimeter (retired in 2009). Providing unprecedented insight into ongoing land and sea ice change in the Arctic, ICESat-2 measures elevation to sub-decimeter resolution, allowing scientists to measure fine variations in ice volume and landscapes in response to warming and environmental change.

To bridge the gap in altimetry data between the retirement of the original ICESat and the launch of ICESat-2, NASA's OIB flew annual surveys of the Greenland Ice Sheet, Alaska glaciers, and Arctic sea ice for 13 years, deploying additional instruments to provide context and data not available by laser altimetry alone. Since its launch, ICESat-2 has continued to provide valuable data to the Arctic research community, and it serves as a point for interagency collaboration.

Focusing on Glacial Change

With an emphasis on understanding glacial processes, including ice melt change, IARPC's Glaciers and Sea Level Team—alongside member agencies—monitored glacial change. This work demonstrates rapid glacial melt in their collective data set and ice loss across the Arctic and global cryosphere. For example, data from the USGS Benchmark Glacier Project, which continued collection of systematic glacial ice mass balance measurements at certain glaciers, revealed remarkably consistent ice loss across maritime and continental glaciers in North America.

This ice melt is not unique. NASA's Gravity Recovery and Climate Experiment (GRACE), the GRACE-Follow on (GRACE-FO)[15], and the Making Earth System Data Records for Use in Research Environments (MEaSUREs)[16] Greenland Ice Mapping Project collectively built a complex record of mass balance for the Greenland Ice Sheet from 1985 through 2019 that shows continued ice loss and seasonality of ice-mass change. This melting is a dominant contributor to sea-level rise—a strong illustration of the global effects of localized melt.



ICESat-2 uses six laser beams to measure the height of ice, as illustrated in this not-to-scale artist's rendering. This illustration is an outcome of the ICESat-2/SCAD Collaborative Student Project.

Walrus cows resting on sea ice south of Nunivak Island, Alaska, while nursing their calves. Credit: Brad Benter/USFWS

Changing Ecosystem Indicators

Changes in plants and animals characterize a shifting Arctic environment. IARPC member agencies and teams engage in a variety of programs to monitor these changes. Addressing varied aspects of the complex terrestrial and marine ecosystems, agencies and collaboration teams have built a better understanding of changing populations, behaviors, and ranges of species important to subsistence hunting and ecosystem management. For example, this work includes bowhead whales, ice seals, walruses, polar bears, waterfowl, caribou, and other Arctic species.

Large-Scale Marine Ecosystem Surveys

Large-scale marine surveys and coordinated observation networks have built complex data sets with insights amplified by IARPC's collaborative effect. Among these is the interagency Distributed Biological Observatory (DBO) Project, which began in 2013 and was renewed for a five-year period in 2017. It studies ecological hotspots in the Pacific Arctic. Data products from the DBO include observations collected not only by satellite observations but also via buoys, moorings, autonomous underwater vehicles (AUVs), and vessel-based sampling. These observations indicate increasing primary (photosynthetic) productivity in the Bering Sea correlated to early sea ice melt.

Concurrently, the BOEM-funded Chukchi Arctic Oceanographic Zooplankton Study (CHAOZ) and the Synthesis of Arctic Research (SOAR)[17] projects, the North Pacific Research Board-funded Arctic Integrated Ecosystem Research Program, and the NOAA-funded Ecosystems and Fisheries-Oceanography Coordinated Investigations (EcoFOCI)[18] aim to connect oceanographic conditions to the food chain. Taken together, these data sets contribute to a more comprehensive understanding of the linkages between physical and biological systems.

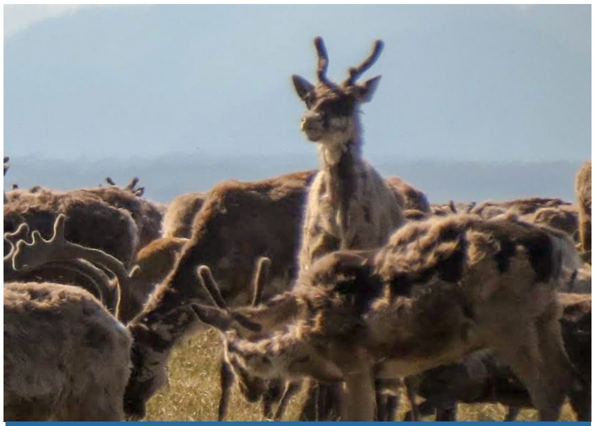
Shifting Behaviors and Ranges on Land

Terrestrially, IARPC member agencies and collaboration teams have quantified behaviors and ranges shifting due to climate change. Such studies show startling changes in population behavior in response to a changing environment. For example, the USGS Changing Arctic Ecosystem initiative measured responses of wildlife species to ecosystem change in the Arctic, providing the long-term foundation needed for ecosystem management decisions.[19]

Of particular interest, the National Park Service in collaboration with international partners undertook the largest study to date of what drives caribou migration, accounting for 80% of North American caribou.[20] The study found that warm, windless summers delay the arrival of caribou at calving grounds, while, at the same time, caribou are calving earlier as the climate warms.

Observations indicate changing vegetative behaviors, as well. Remote sensing via aircraft or satellite, informed by NSF-sponsored fieldwork at more than 20 Arctic sites, found that climate warming in areas receiving more snow led to a more rapid tree line advance within the Brooks Range of northern Alaska.

White spruce, a species that may have been absent from the region throughout the Holocene (the current geological epoch), was found by NSF researchers to be advancing northward at more than 300 meters a year. As tree lines move, warming rates are amplified. Soil and air temperature data from 106 sites synthesized by NPS and the Permafrost Carbon Network showed higher soil temperatures under tall trees and shrubs than other vegetation types.



Research shows that warm, windless summers delay the arrival of caribou at calving grounds, while, at the same time, caribou are calving earlier as the climate warms. Credit: Andrea Medeiros/ USFWS

Case Study

Monitoring the Effects of Thawing Permafrost

As temperatures rise in the Arctic, permafrost thaws at an accelerated rate, often with significant consequences for the local environment. Agencies and collaboration team members associated with IARPC have diligently identified and quantified these changes and their effects over the last five years, exemplified by collaborative programs like NGEE Arctic[21] and NASA's ABoVE Campaign[22] (Chapter 3), which combine field campaigns, experiments, observations, and synthesis of existing data sets to advance models of Arctic permafrost thaw.

Warming permafrost has the potential to release dangerous contaminants once locked within the frozen matrix. Among these, mercury—which accumulates in Arctic systems—has been shown by USGS to be released from thawing permafrost. This poses a risk to ecosystem health. As a result, the U.S. Department of Defense (DOD) has used comprehensive studies to determine bioremediation techniques for legacy hydrocarbons within the Arctic, using remote sensors and tracer dye to detect contaminate pathways within degraded permafrost.

In addition to contaminants, greenhouse gases that amplify global warming are released from permafrost in increasing volumes as Arctic wildfires also become more common. The Terrestrial Ecosystems Collaboration Team demonstrated that between 2001 and 2019, Alaska wildfires released 3.3 billion metric tons of greenhouse gases from permafrost, which would be equivalent to about half of the annual GHG emissions in the United States.[23]

CH.3 Modeling and Projecting the Future Arctic

Gyldenlove Glacier, southeast Greenland. Credit: Michael Studinger/NASA Goddard

Over the last five years, IARPC Collaborations has supported significant advances in modeling the current Arctic and predicting future conditions by facilitating communications among experts, shared data sets, and interagency project coordination to improve capabilities.

This work aligns directly to all primary policy drivers of the Arctic Research Plan—addressing connections between the Arctic and the rest of the globe, focusing on environmental stewardship, and improving predictions of future Arctic conditions for improved security and human health. To this end, the following work fulfills several research goals of the Arctic Research Plan, including improved understanding of atmospheric, sea ice, glacial, marine, terrestrial, and permafrost systems. It emphasizes efforts to strengthen coastal resilience within the Arctic environment.

Employing Models to Understand Our Arctic System and Global Climate

What happens in the Arctic does not stay in the Arctic. To understand connections between the Arctic and the rest of the planet, scientists use models, projections, and predictions supported by IARPC Collaborations. These are valuable forecasting tools used across multiple time and space scales—from daily weather conditions to climate projections hundreds of years in the future.

Arctic warming affects not only Alaska, but the rest of the United States and the entire planet. Thawing permafrost releases previously trapped greenhouse gases carbon dioxide and methane, contributing to further global warming (a, leftmost circle). Increased frequency of wildfires in the Arctic further increases permafrost thaw and gas release. Glaciers and land ice, in particular the Greenland Ice Sheet, also experience increased melt as a result of warming (b, center circle) (c, rightmost circle) Significant ice melt is a driving factor for sea level rise, which is experienced globally and threatens coastal communities across the world. As warming reduces the extent, thickness, and duration of Arctic sea ice cover, the Arctic Ocean is becoming increasingly accessible to global shipping, introducing new routes to potentially shorten shipping times and straining Arctic search and rescue infrastructure.

Predicting Conditions Beyond the Arctic

Ocean and sea ice condition observations are integrated into models that are then used to make predictions of weather and climate across the globe. For example, NOAA's Real-Time Ocean Forecast System[24] and the National Weather Service's forecasts, which use satellite data and include models of global sea ice and ocean processes, operate from Alaska to the Great Lakes to the West Coast. At the opposite pole, the National Ice Center uses the U.S. Navy's Early System Prediction to support science efforts, like the resupply of NSF's McMurdo Station.

Wave modeling and improved predictions of storms and impacts help improve strategies for short- and long-term coastal resilience, a primary goal of the Arctic Research Plan. Multiple agencies developed WAVEWATCH III, a global network of predictions designed to forecast ocean waves, to provide a comprehensive storm-modeling framework with direct interactions between the ocean and atmosphere.[25] WAVEWATCH III incorporates models of the Arctic Ocean into global system models to improve understanding of climate change and its effects in lower latitudes.

Anticipating Global Change

Models highlighted through IARPC group collaboration have supported several international projections of future climate and its effects with significant representation of Arctic processes. In conjunction with the 6th Model Intercomparison Project (CMIP6) with IARPC agency participation, several evaluations of predictive models related to the Arctic were conducted, including assessments for sea ice and the Greenland Ice Sheet permafrost.

For example, the Ice Sheet Model Intercomparison Project of CMIP6 generated a consensus estimate of the amount of ice lost from the Greenland Ice Sheet by 2100 and estimated 90 ± 50 mm contribution to sea-level rise assuming business-as-usual human emissions.[26] Models of the Greenland Ice Sheet showing similar contributions to sea level rise predict that Greenland will likely become ice-free within the next thousand years without substantial reductions to greenhouse gas emissions. In fact, the Greenland Ice Sheet is now experiencing ice loss faster than any period in the last 12,000 years.[27]

Continuity and Improvement of Sea Ice Projections for Global Communities

Projections of ice-free summers in the Arctic Ocean are commonly used to represent broader warming and climate change. Underlying these projections are complex models. IARPC communities contributed to the maintenance and development of such models over the last five years.

In fact, IARPC has enhanced connections between the observation and modeling communities, improving our confidence in these projections.

Developing CICE

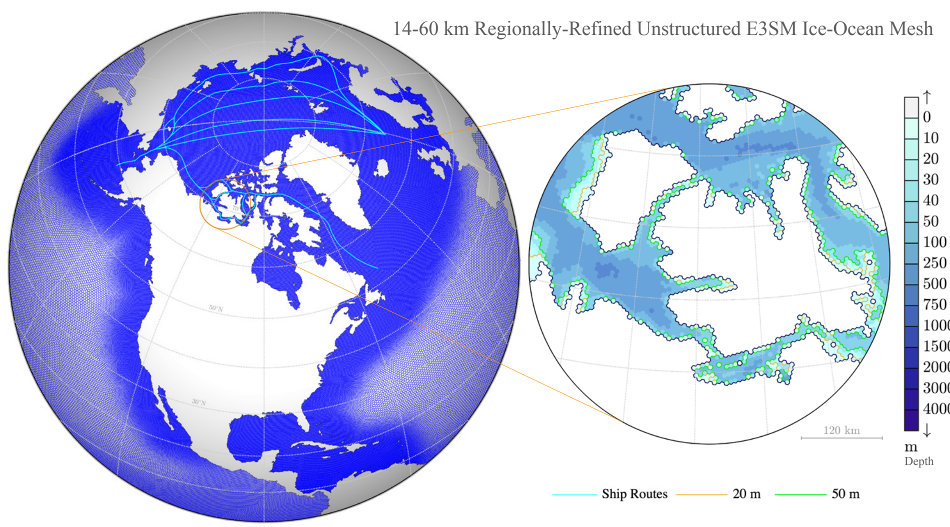
Throughout the Arctic Research Plan, agencies and researchers working with IARPC helped support the continued development of the world's best-known sea ice model, the DOE-Los Alamos Sea Ice Model, better known as Community Ice Code or CICE. Notably, the last five years saw the first steps of the CICE consortium, which represents multiple modeling centers, agencies, and nations working to maintain and improve scientific sea ice model development.

Many IARPC agencies have participated in the continuing and collaborative development of CICE. For example, the U.S. Naval Research Laboratory scientists collaborated with the National Ice Center and the Canadian Ice Survey weekly to chart data and determine physical parameters of landfast ice for incorporation into the CICE6 model. Likewise, BOEM contributed to development of a coupled ocean ice code modular ocean model (MOM6).

A Community of Models

In addition to CICE, several models and networks run collaborative projections of Arctic Ocean and sea ice characteristics. The Sea Ice Prediction Network (SIPN)[28] continues to run the multi-agency and community-based sea ice outlook, which has benefited from increased collaboration between the observing and modeling communities enabled by IARPC's Sea Ice Collaboration Team.

As an example, DOE released its flagship Earth system model, Energy Exascale Earth System Model (E3SM), which represents the Arctic at resolutions as high as 6km in fully coupled simulations.[29] E3SM is being used to develop improved ocean-mixing schemes, river-ocean coupling, and sea ice interactions, informed by observational data, including those collected during the international MOSAiC expedition in 2019-2020. Similarly, NSF's Community Earth Systems Model (CESM) has a new high-resolution global model that is also eddy permitting in the Arctic, and NASA's new version 2 of its subseasonal to seasonal prediction system also contributes projections to SIPN.[30]



The Model for Prediction Across Scales (MPAS) modeling framework is a multi-purpose computational code for simulating various parts of the Earth system at variable resolution on unstructured grids, including the Arctic refined mesh shown above that resolves high northern shipping routes. MPAS ocean, sea ice, and land ice cores are currently employed by the Energy Exascale Earth System Model (E3SM). Credit: DOE

Coastal erosion reveals the extent of ice-rich permafrost underlying active layer on the Arctic Coastal Plain in the Teshekpuk Lake Special Area of the National Petroleum Reserve-Alaska. Credit: Brandt Meixell/USGS

Modeling capabilities like CICE, CESM and E3SM, and model intercomparison forums like SIPN that incorporate in-situ and satellite measurements of sea ice into energy budget calculations, have led to foundational improvements in our understanding of the Arctic system.

Analysis of satellite data and energy budget models performed by NOAA, for example, has shown that sea ice loss—not snow—has contributed the most significant change to albedo feedback due to climate change.

Understanding the Terrestrial Carbon Cycle

Permafrost and terrestrial ecosystems hold a large pool of carbon that is globally significant for its ability to contribute potent greenhouse gases, yet elements of how warming and thawing permafrost change the Arctic carbon cycle remain unknown. Over the last five years, the Arctic research community has made significant improvements in understanding the Arctic terrestrial carbon cycle by incorporating observations in enhanced models to add complexity and reduce uncertainties, in turn informing a wide variety of chemical and biological processes.

Constraining the Flux of Carbon Dioxide

Key elements of the terrestrial carbon cycle have been constrained through observations and incorporated into flux projections and carbon flow models, which improves the predictability of fluxes of critical greenhouse gases like methane. The Next Generation Ecosystems Experiment (NGEE Arctic) and NASA's Arctic-Boreal Vulnerability Experiment (ABoVE) are collaborating together to improve Arctic terrestrial systems' representation in E3SM. Using landscape classification schemes and improved predictability of large-scale carbon dioxide (CO_2) and methane (CH_4) flux projections, NGEE Arctic helped resolve uncertainties in E3SM models by quantifying decomposition of historically stable carbon and quantifying CO_2 uptake by plants via gas-exchange experiments. Similar work in Alaska by NSF investigators showed, for the first time, that ancient (> 4000-year-old) dissolved organic carbon soils are readily oxidized by sunlight when flushed into lakes and rivers, indicating current model estimates of permafrost carbon released as a result of warming are likely too low.[31]

Case Study

Improving Communication Among Observational Scientists and Modelers to Advance Predictive Modeling of Marine Biogeochemistry

The leaders of the Marine Ecosystems and Modeling collaboration teams hosted a series of webinars to encourage communication among those making oceanographic observations and those who develop models to represent the interactions among the physical and biological aspects of the marine environment. It was recognized that observational scientists could inform modelers about recent observations and experimental results that could improve model design. They could also provide real world data for validating models to assess their performance.

Modelers could provide tools to test hypotheses about the environmental processes that observational scientists strive to understand and in turn, deliver model-based guidance on the design of observational campaigns. To do this successfully, the modeling and observational communities need to work together, using an integrated and iterative approach.

IARPC created opportunities for these scientists to interact to advance the capacity for predictive modeling. Information was shared about the Unified Forecast System that aims to more rapidly transition models from research to operations, building capacity for ecological forecasting. The conversations generated several ideas about how Federal agencies could cooperate to advance this type of work in the future; some are presented in a white paper.

This vital work builds towards forecasting marine conditions that affect livelihoods, public safety, and improving our understanding of marine ecosystems in an ecological sense. It builds the foundation for predicting how, when, and where the base of the food web—which sustains the fish and marine mammal populations upon which people rely—develops. It also improves the capacity to predict harmful algal blooms that can be deadly to humans and wildlife.

Projecting Effects of Permafrost Loss

With better quantification of uncertainty, improved models allow a better understanding of the effects of thawing permafrost, highlighting the irreversible and global scale importance of thaw. A survey of 44 leading permafrost experts using data from USGS and NPS researchers estimated future carbon fluxes and suggested that peatlands hold an estimated 100 billion tons of carbon that could be released by 2100 and lead to enhanced warming.[32] This process is already inevitable for many regions in Alaska: an analysis by DOD scientists and collaborators indicates certain regions within Alaska have crossed a tipping point of permafrost thaw with irreversible loss.

CH.4 Applying Research to Human Needs

Family time at Nalukataq is the most important component. At the site of Nalukataq in Utqiaġvik, Alaska. Credit: Elizabeth Eubanks/ PolarTREC 2008, Courtesy of ARCUS

Within the Arctic Research Plan, IARPC emphasized the application of science for community needs, listing enhancing human well-being as a primary policy driver for research. The Arctic research community responded, focusing on building resilient communities across the U.S. Arctic by helping to preserve cultural and Indigenous knowledge, contributing new knowledge in human health and food security, and advancing science of the built environment. In developing these projects, the community addressed key research goals of the Arctic Research Plan, most notably enhancing understanding of human health determinants, strengthening coastal resilience, and improving environmental intelligence.

Preserving Cultural History for the Future

To support human and ecosystem health in a rapidly changing Arctic, it is urgent to preserve natural history and Indigenous knowledge across communities. The work of IARPC member agencies and collaboration teams helped to catalog, interpret, and expand access to cultural knowledge across Arctic communities by documenting important traditions and knowledge and highlighting their role in the modern world.

Hubbard Glacier from Russell Fjord, Yakutat Ranger District. Credit: Wendy Zirngibl/USFS

Documenting Changing Environmental Knowledge

The Arctic research community documented historical Indigenous knowledge and evolving relationships between Indigenous peoples in the Arctic and their changing environment. IARPC member agencies and collaboration teams investigated cultural ecology—human adaptation to physical environments—from multiple points across the long history of human habitation in the Arctic.

Looking at historical data across the circumpolar Arctic, a network of anthropologists, archaeologists, biologists, and Indigenous knowledge holders from multiple nations explored project explored the roles of people, climate, and ecosystem change in the historical dynamics of key Arctic wildlife species to understand the causes of historical 'crashes' – rapid loss of animal and human populations. The seven-year research project was published as a book by the Smithsonian Institution. The NOVA special, Polar Extremes, featuring Smithsonian Natural History Museum director Kirk Johnson, bought new understanding and public awareness of Arctic history, geography, cultures, and climate implications for the future to a broad audience.

In southeast Alaska, a project from the Smithsonian and Yakutat Tlingit Tribe demonstrated Indigenous adaptation as glaciers have retreated from Yakutat Fjord over the last 800 years. The project used environmental studies, archaeology, and community interviews.

In northern Alaska, Project Jukebox continued a record of oral history cataloged since 1978.[33] Iñupiat and other North Slope residents were asked to share personal observations and community knowledge of changing sea ice conditions near Utqiaġvik and Kotzebue. This record helps preserve Indigenous knowledge and documents the evolving relationship between Alaska residents and their environment.

In addition to documenting past adaptations to a dynamic environment, IARPC member agencies and collaboration teams worked with Indigenous communities in Alaska to preserve and perpetuate traditional practices diminished in the wake of colonization. Yup'ik grass basketry artists taught weaving of twinned grass bags for public recording, while Ahtna and Dena'ina artists demonstrated tanning and sewing of moose hide in the traditional Dene way for the Arctic Studies Center's *Material Traditions* series.

Human Health and Food Security

IARPC's collaborative nature brought together multiple studies and investigations of the health of Arctic residents within a holistic framework. These projects were largely focused on Indigenous communities, addressing determinants of health that are uniquely affected within the context of a changing climate and Arctic system, such as food security.

Addressing Holistic Human Health

With a focus on regional partnerships, IARPC member agencies worked with partners in Alaska and the rest of the United States to help identify, quantify, and analyze determinants of holistic human health for Indigenous and other Arctic residents. Tackling the complex nature of human health from multiple angles, the synthesis of these projects provides a broader, better look at the causes and effects of colonization, resource extraction, and a changing environment on the health of Indigenous Peoples in Alaska.

While 58% of North Slope residents reported being very satisfied with life, IARPC member agencies and teams assisted in the dissemination of research findings regarding human resilience within Arctic communities. They identified factors that lead to community resilience. One product of this effort was a web-based toolkit called RISING SUN that assists communities in suicide prevention and response.

In the first year of the Arctic Research Plan, BOEM commissioned a sweeping survey of social indicators of health within Alaska coastal communities that indicated that cultural continuity, economic well-being, and local control correlated to the greatest overall well-being.[34]

Concurrently, collaborative efforts in partnership with state and tribal organizations were coordinated in IARPC team-organized meetings on One Health, a transdisciplinary focus on integrated human and environmental health. Similar partnerships cataloged and prioritized emerging zoonotic diseases that could become widespread by modern means of transmission and could be impacted by changing climate conditions. This work included preparedness plans for seven zoonotic diseases of most significant concern to the state.

Yup'ik culture-bearers and students who demonstrate how to harvest, process and twine taperrnaq (coarse seashore grass), produced by the Smithsonian Arctic Studies Center in Alaska. Credit: Smithsonian Arctic Studies Center video

Food Security in the Arctic

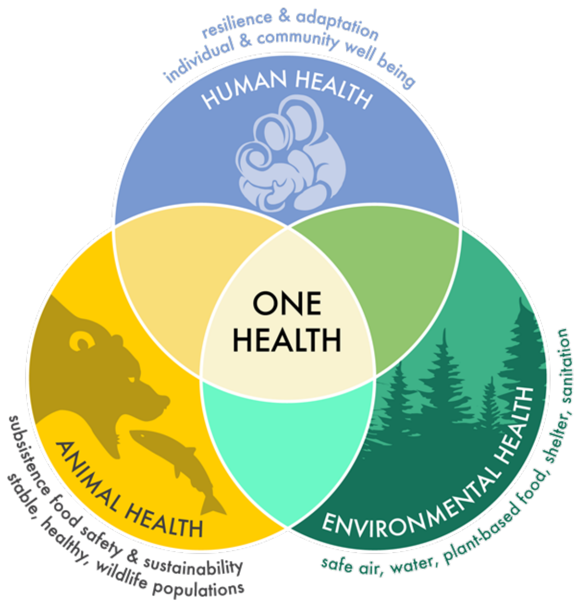
The IARPC research infrastructure focused on bringing together fundamental observations and models to predict and respond to the changing nature of Arctic food security. Demonstrating the united focus, the Data Collaboration Team helped establish a governance linkage between IARPC and the Sustained Arctic Observing Network (SAON), which in turn worked in collaboration with IARPC participants like the Arctic Observing Systems Sub-Team, to prioritize food security and Indigenous knowledge and direct participation from Indigenous Peoples as a lens for identifying shared Arctic variables. Food security issues also impact access to resources. To support these discussions, the IARPC Sea Ice Collaboration team invited programs such as the Sea Ice for Walrus Outlook (SIWO)[35], which includes Indigenous experts on sea ice, to share information about ice and weather observations that support safety at sea during subsistence hunts. Additional work from IARPC researchers from the Marine Ecosystems Collaboration Team and others have focused on observing these changes, especially within critical nodes—like Arctic cod—to link to food security within the Arctic and beyond.

The Built Environment and Physical Infrastructure

Maintaining infrastructure within the harsh Arctic environment requires a deep understanding of the baseline physical environment and unique modes and techniques for adaptation. Together, scientists associated with IARPC have an advanced understanding of cold-environment engineering in the face of shifting permafrost and developed tools for better monitoring marine infrastructure and impacts on the ocean.

Preparing Resilient Infrastructure

Broad surveys of the changing environment focused on potential infrastructure impacts provided a better



One Health recognizes the interdependence of human, animal and environmental health, and that a holistic approach to the well-being of all will lead to improved health outcomes and enhanced resilience. Credit: University of Alaska Fairbanks Center for One Health Research

Salmonberries at the Izembek National Wildlife Refuge. Credit: Kristine Sowl/USFWS

baseline for improved coastal resilience in the future. Several major surveys of changing coastlines were performed by member agencies in alignment with the Arctic Research Plan's goal of building resilient communities.

The USGS National Assessment of Shoreline Change on the Coast of Alaska quantified shore change rates to improve coastal village resilience and support long-term planning for responses to the changing environment.

InteRFACE, the Interdisciplinary Research for Arctic Coastal Environments project funded by DOE, likewise surveyed drivers and patterns of coastal change as it may interact with settlements and economic development in northern Alaska.[36] Similar results were incorporated into a public report produced by the Denali Commission in collaboration with the U.S. Army Corps of Engineers to assess threats from the changing landscape, including those of permafrost thaw to critical infrastructure.

Complementing these surveys, environmental threat assessments were performed for 187 villages in Alaska at risk for permafrost degradation, coastal erosion, and flooding to provide accurate threat levels. These baseline threat assessments provided foundational context for continued adaptation to changing conditions. For example, advances in cold-environment engineering for airfield construction and other permafrost foundations were investigated and actualized, as exemplified by the Thule Air Base Greenland, which now has long-term, climate neutral foundation solutions.

Improving Arctic Shipping

Improved national and regional security, including advanced emergency preparation and response capabilities, was identified as a key policy driver of the Arctic Research Plan. As sea ice retreat opens the Arctic Ocean to global shipping traffic and military intervention, the IARPC member agencies and collaboration teams have focused on improving Arctic domain awareness, as well as monitoring and safety of both ships and the environment they traverse.

To address this goal, IARPC member agencies and collaboration teams have focused on improved monitoring of the Arctic environment for potential hazards to ships and national security, and on making the data accessible for Arctic residents. Among these improvements, a newly developed Arctic All-Hazards GIS Platform for vessel tracking uses cartography to streamline vessel traffic monitoring. Additional vessel monitoring platforms focus on providing such data directly to communities in Alaska.

The Data Collaboration Team helped to disseminate maritime vessel data among Alaska residents via the Arctic Vessel Monitoring Geofencing technology and Marine Exchange of Alaska to improve awareness of vessel movements and deconflict subsistence hunting and shipping.[37]

Maintaining National Security

IARPC has also supported research that helps to improve U.S. national security in the Arctic domain. In support of the Department of State-led Extended Continental Shelf (ECS) Task Force,[38] USGS is the Federal lead for providing the marine geologic and geophysical data, interpretations, and products to substantiate U.S. rights to an Extended Continental Shelf consistent with international law as established by the United Nations Convention on the Law of the Sea (UNCLOS). USGS has completed all data collection, analyses, and initial interpretations to establish an Arctic ECS consistent with ECS Task Force legal and policy interpretations and strategies.

U.S. Coast Guard Petty Officer 2nd Class Richard Wells pulls himself out from the Arctic Ocean during ice rescue training.
Credit: NyxoLyno Cangemi/U.S. Coast Guard

Case Study

A Rapid Response to Harmful Algal Blooms

With warming seawater and diminishing ice cover, the Bering and Chukchi seas have become increasingly susceptible to the formation of harmful algal blooms (HABs): rapid growths of planktonic algae that can be toxic to marine and human life. Across IARPC, understanding the causes and impacts of Arctic HABs has been a priority for collaboration teams. The Coastal Resilience, Environmental Intelligence, Marine Ecosystems, and Sea Ice collaboration teams held several joint meetings on the topic with input from researchers and Arctic residents to identify where future observations, models, predictions, and studies are needed to understand how changing conditions may affect the intensity and distribution of HABs.

When record-low sea ice in the Bering Sea led to increased vulnerability to HABs, NOAA Research's Arctic Research Program used IARPC Collaborations to assist with a rapid response to the 2018 emerging HAB situation. Scientists and agencies met monthly via the Collaborations platform to exchange information and coordinate sample collection in surface waters and sediments in the Bering and Chukchi seas. The Bering Sea Action Team (BSAT), established by IARPC and led by NOAA Alaska Regional Collaboration Team Leadership, brought Federal agencies together to identify their operational and resource management research needs created by the sudden ecosystem shift in 2018 and to influence agency decisions enabling the collection of time-sensitive data and information not part of existing studies.

Conclusion: Change, Uncertainty, and Opportunity

Continued work to understand the Arctic system is an urgent need. As highlighted in the 2017-2021 Arctic Research Plan, no region on Earth is warming faster or seeing more rapid climate, environmental, and socioeconomic change. IARPC has supported tremendous advancement in understanding the changing Arctic system, and we have strengthened the research infrastructure needed to adapt in an uncertain future.

The accomplishments and achievements presented in this report demonstrate the successful execution of the 2017-2021 Arctic Research Plan. Agencies and collaboration team members working with IARPC quantified the Arctic system through observations, built deeper process knowledge through experimental research, advanced model capabilities by more accurate representations of some key Arctic processes, and strengthened human resilience through relationships and applied research. All this work was enhanced by IARPC coordination and collaborations.

The total impact of IARPC is larger than can be conveyed in any single report, both in the number of projects accomplished and in their rippling effects across Arctic and global life. A more profound understanding of the Arctic system reduces insecurity and dampens environmental, economic, and security risks associated with climate change. In coordinating agency research across holistic topics, IARPC has helped amplify this effect by reducing inefficiencies and building a body of knowledge greater than its individual parts. In turn, this work provides a better foundation for decision-makers as they seek to address the continuing challenges within the Arctic.

With rapid Arctic change comes uncertainty, but also opportunity. As IARPC looks toward the next five-year Arctic Research Plan, the work established between 2017 and 2021 will provide a strong foundation for continuing to improve understanding of the Arctic system. IARPC will continue to prioritize the needs of all who live in the U.S. Arctic, emphasizing the use of science and research to improve decision-making and everyday life.

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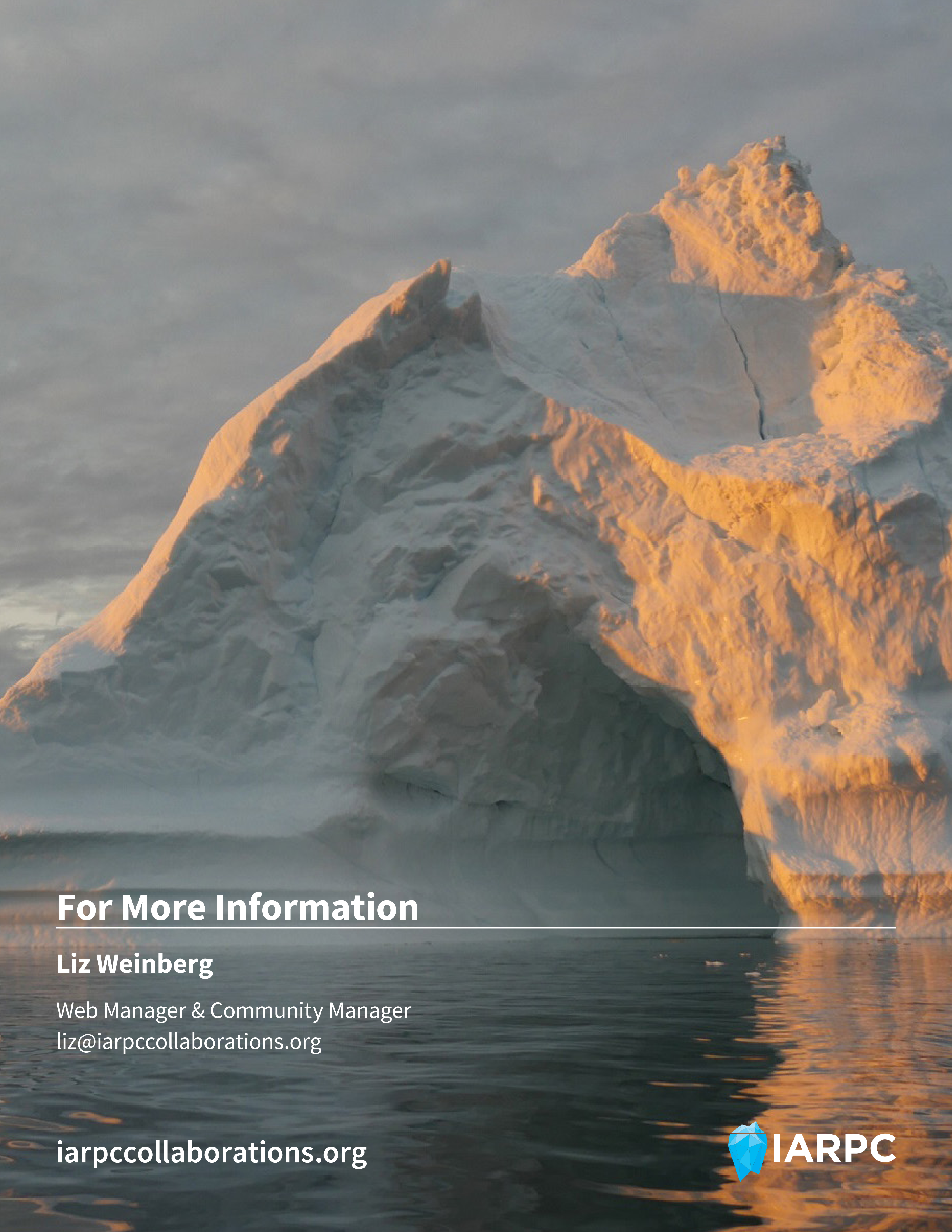

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