ON THE NEED TO ESTABLISH AND MAINTAIN A SUSTAINED ARCTIC OBSERVING NETWORK

Prepared by

THE US ARCTIC OBSERVING NETWORK,

on behalf of the

INTERAGENCY ARCTIC RESEARCH POLICY COMMITTEE

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

DECEMBER 2022

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

December 15, 2022

Dear Members of Congress and the Arctic Research Community,

We are pleased to submit the report, *On the Need to Establish and Maintain a Sustained Arctic Observing Network*. This report was prepared in response to House Report 117-97, which accompanied the Consolidated Appropriations Act, 2022 (Public Law 117-103), and which "recognizes the significant impacts of the changing climate in the Arctic" and directs the Office of Science and Technology Policy (OSTP) to prepare "a report on the need to establish and maintain a sustained Arctic observing network, including recommendations on the implementation and construction of such a network."

This report describes the need and opportunity to advance Arctic observations to achieve Federal priorities, such as national security, understanding and addressing climate and environmental change, improving the lives of Arctic residents, and creating broad, cost-effective, and sustainable research partnerships. Scientists have documented that the Arctic is warming 3-4 times faster than the rest of the world, with serious impacts to people, communities, infrastructure, weather, food security, national security, and more. As Congress has recognized, our nation's ability to understand, predict, prepare for, and respond to these changes is hampered by sparse observations in the region. The report articulates the compelling need to improve and link our observing systems to protect the well-being of Arctic residents and the nation.

This report reflects the cooperative efforts of many Federal agencies and highlights the agencies' ability to come together around shared priorities. It sets the stage for continued partnership and expanded observational networks and presents a clear vision for a sustained Arctic observing network.

We appreciate your support as we work together to build a stronger foundation for some of the most pressing and challenging research of our time.

Sincerely,

Arati Prabhakar
Director, White House Office of Science and Technology Policy

Sethuraman Panchanathan
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 via 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, provides for a comprehensive national policy dealing with national research needs and objectives in the Arctic. ARPA establishes an Arctic Research Commission 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 chair of the committee.

About the U.S. Arctic Observing Network

The U.S. Arctic Observing Network (U.S. AON) was established in September 2016 during the White House Arctic Science Ministerial. On this occasion, the U.S. AON coordinating concept was formally adopted under joint mandates from the White House Arctic Science Ministerial and the international Sustaining Arctic Observing Networks (SAON). Each called for improved capacities for national coordination. The U.S. AON aims to improve Arctic observing and data management activities through planning and partnerships across agencies, observing networks, and data systems. Policy guidance for

U.S. AON and alignment with agency goals are provided through its interagency U.S. AON Board, composed of representatives from U.S. Federal agencies. The U.S. AON is also responsive to recommendations from the National Academies' studies, the Study of Environmental Arctic Change (SEARCH) program recommendations, the U.S. Arctic Research Commission, and IARPC. As a recognized sub-body of IARPC, the U.S. AON is engaged with non-Federal partners through the IARPC Collaborations forum, an innovative platform that brings together researchers, Federal agencies, and communities to implement IARPC's Arctic Research Plan.

About This Document

This report was developed by the US Arctic Observing Network on behalf of the Interagency Arctic Research Policy Committee, and is published by OSTP. The report identifies potential investment opportunities that will help to inform the Federal budget development process, but it is not a budget document and does not imply approval of any specific action or investment. All activities and recommendations included in the report are subject to resource constraints and weighing of priorities as part of the annual budget formulation process, as well as the availability of appropriations provided by Congress.

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1. Executive Summary

The Arctic is warming at least four times the rate of the rest of the planet, with consequences for security, livelihoods, ecosystems, and biodiversity, yet it remains inadequately observed by conventional observing technologies. Arctic Indigenous Peoples and other northern residents are on the front lines of these changes, and all U.S. Americans are contending with Arctic change through impacts to weather and climate patterns, food webs, sea level rise, and more. To advance Arctic observing networks, this report bases its recommendations on a survey of agencies across the U.S. Arctic Observing Network (AON) Board, a literature synthesis of current assets, and public comments for the Interagency Research Policy Committee (IARPC) Arctic Research Plan 2022-2026.

Current Arctic observations yield invaluable information and data that influence global models and forecasts, national security decisions, community resilience, and economic prosperity. However, these capabilities are inadequate to meet growing data needs in light of rapid climate change, ecosystem shifts, and heightened homeland security priorities. A sustained Arctic observing network must build on current efforts to support fundamental understanding of environmental change and to inform decision makers across scales. This report recommends a focus on the following prioritized needs: (1) Support for coordinated, integrated, and sustained critical observations and infrastructure; (2) Development of a shared data management system that is open, easily discoverable, accessible, and usable across observing networks; (3) Prioritization of human and technological capacity building; and (4) Closure of observational gaps in marine, cryospheric, terrestrial, atmospheric, and social systems for decision-making on climate resilience and national security. Some of the critical infrastructure needed to achieve this include: satellites, aircraft, and *in-situ* technologies for data on sea ice conditions and wildland fires; vessels for oceanography, fisheries, and harmful algal bloom monitoring; community-based observations of marine and terrestrial mammals; atmospheric drop sondes and meteorological balloons for understanding the connection between Arctic and mid-latitude weather patterns; and terrestrial stream gages and coastal water level monitoring stations for early flood warnings.

This report concludes that an Implementation Plan is needed to provide a system-level view of existing activities, a policy-driven gaps assessment, a rigorous set of requirements for observing and data systems derived from that assessment, and specific action plans that outline agency responsibilities for coordination, governance, and management of such a sustained Arctic observing network. This report recognizes that developing and implementing a sustained U.S. AON must advance the capacity for equitable engagement of Indigenous communities and Indigenous Knowledge, as appropriate, in its design and development.

2. Introduction

The nation's ability to monitor, detect, and understand marine, terrestrial, and atmospheric changes and their implications for the rest of the planet is driven by capabilities of the observing facilities in the Arctic. On behalf of the Interagency Arctic Research Policy Committee (IARPC), the United States Arctic Observing Network (U.S. AON) Board prepared this report for the White House Office of Science and Technology Policy (OSTP) in response to a requirement of a Committee Report accompanying the Fiscal Year 2022 omnibus appropriations law (H.Rept. 117-97) describing the need for a sustained Arctic observing network. The report presents an overview of the desired state of U.S. Arctic observing assets, highlights exemplary current U.S. Arctic observing assets, and calls for an Implementation Plan to achieve the desired state.

Due to the rapid timeline in developing this report, the writing team relied on existing key reports and plans identified by the U.S. AON Board, results from an ad hoc survey of U.S. Federal agencies, and a collection of synthesized public comments recently gathered during the development of the IARPC Arctic Research Plan for 2022-2026. The writing team acknowledges the lack of explicit public outreach during report development, which was due to the rapid timeline, and the need for meaningful consultation and engagement of all stakeholders and rights holders, including local and Indigenous Arctic residents, before any implementation.

*Note: Throughout this report, we will refer to the vision of an internationally coordinated Arctic observing network as **AON**, the United States portion of the AON as **the U.S. AON**, and the body responsible for coordinating Arctic observations and for the authorship of this report as the **U.S. AON Board**.*

2.1 Defining the Arctic and the U.S. Arctic Observing Network

The Arctic Research and Policy Act of 1984 (ARPA) established the U.S. Arctic Research Commission (USARC) and IARPC to guide and implement national policy and plan for basic and applied Arctic research. The ARPA also defined the geographic parameters of the **Arctic** (see Fig. 1). Further, **observing** systems are "sensing elements that directly or indirectly collect observations of the Earth, measure environmental variables, or survey biological or other Earth resources" (IDA STPI & SAON, 2017). **Networks** take the lead in standardizing, coordinating, and enhancing observing efforts to increase data accessibility and improve the ability to detect and understand trends.

The concept for an Arctic Observing Network (AON) was inspired by the advent of the 2007-2009 International Polar Year, after a National Research Council report recommended that the International Polar Year "should be used as an opportunity to design and implement multidisciplinary polar observing networks that will provide a long-term perspective" (NRC, 2004). The critical functions of the AON are to collect, check, organize, and distribute Arctic observations while taking the necessary measures to adapt and improve the network continuously. Internationally, science diplomacy and coordination of the AON have proceeded under the Sustaining Arctic Observing Networks (SAON) activity, a joint initiative of the Arctic Council and the International Arctic Science Committee (IASC) (Appendix, Fig. A). Nationally, coordination is driven by the U.S. AON, with guidance provided through its interagency U.S. AON Board, composed of representatives from U.S. Federal agencies (Appendix,

Table A). Meanwhile, research coordination has been realized through the National Science Foundation (NSF) Arctic Observing Network Program, the National Oceanic and Atmospheric Administration (NOAA) Arctic Research Program, the Study of Environmental Arctic Change (SEARCH), and through interagency dialog.

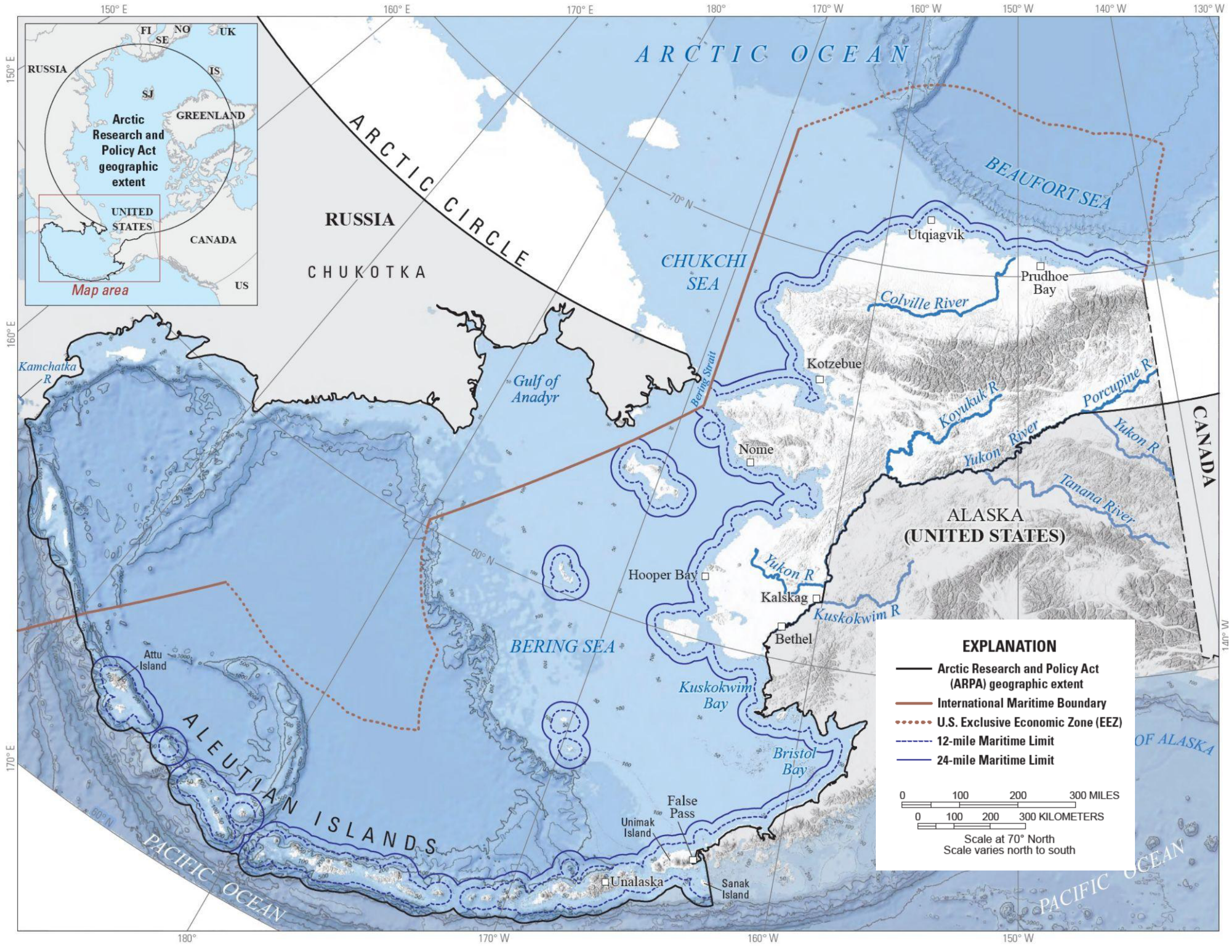

Fig. 1. The Arctic Research and Policy Act Region—U.S. Territorial Limits (modified from Williams & Richmond, 2021).

2.2 Strategic Policy Drivers for the AON Design

According to research published in Nature Communications Earth & Environment, the Arctic is warming at least four times the rate of the rest of the planet, with consequences for national and economic security, livelihoods, ecosystems, and biodiversity in Alaska and the rest of the United States (Rantanen et al., 2022), yet it remains one of the most sparsely observed regions of our planet. For example, the United States Geological Survey (USGS) streamgage network in Alaska has a density that is only 6 percent of the density found in the lower 48 states (Fig. 2). Streamgages collect real-time water flow data in rivers and streams which inform early flood warning. We do not suggest that the streamgage network be replicated in Alaska; instead, the map demonstrates the observational capacity and infrastructural challenges in the Arctic. Independent research by the Science and Technology Policy

Institute (STPI) underlines that strengthening and integrating Arctic observations help with disaster preparedness among many other benefits (IDA STPI & SAON, 2017). In light of the current inability to access Russian territory, which represents more than 50 percent of the Arctic, there is an even greater need for observations from satellite- and airborne-based assets.

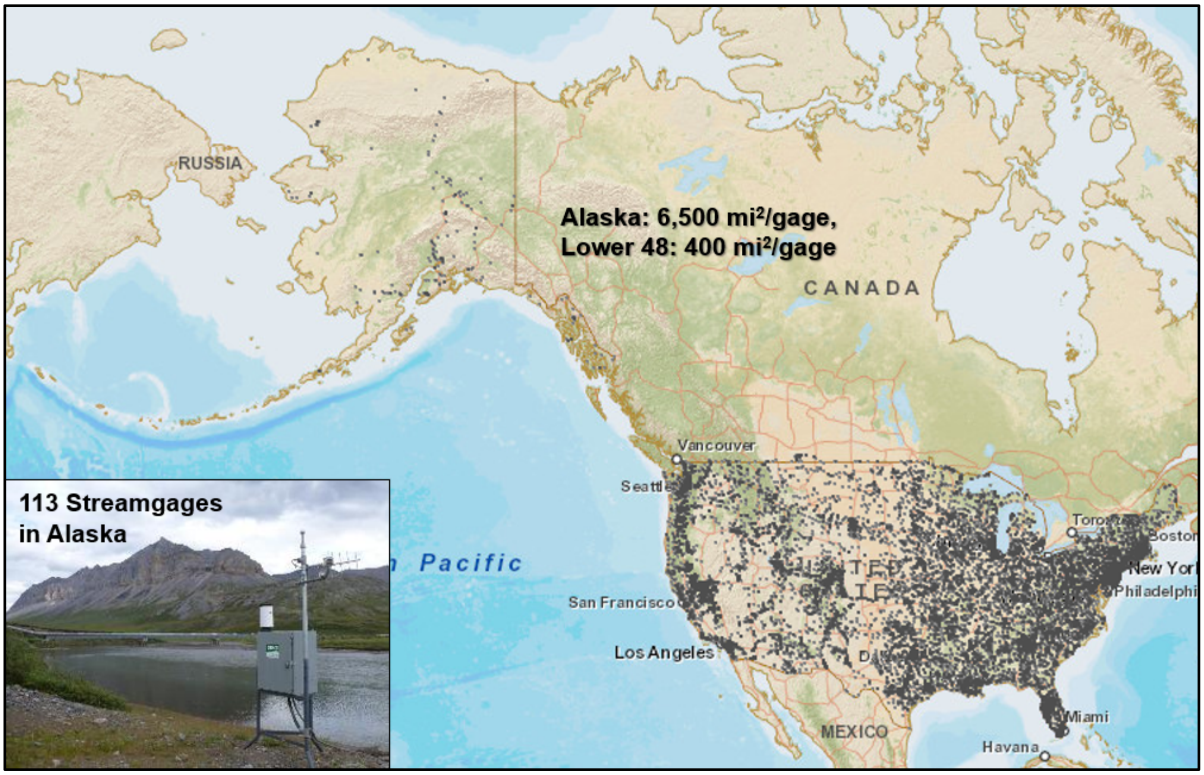

Fig. 2. Illustration of USGS streamgage coverage comparing the Arctic and Alaska to the lower 48.

Growing regional instability poses a major challenge to Arctic observing. The National Strategy for the Arctic Region (NSAR) released by the White House in October 2022 states: “The United States seeks an Arctic region that is peaceful, stable, prosperous, and cooperative.” To achieve that vision, the NSAR articulates four foundational pillars: (1) Security, (2) Climate Change and Environmental Protection, (3) Sustainable Economic Development, and (4) International Cooperation and Governance (The White House, 2022). To realize the objectives within each pillar, strategic investment in U.S. Arctic observing infrastructure and capabilities and capacity building in local communities is needed.

In addition to Federal policy drivers, this report is informed by perspectives on priority research areas drawn from academic scientists and institutions, Indigenous organizations and individuals, the State of Alaska, and private sector and nonprofit organizations that are reflected in the IARPC Arctic Research Plan 2022-2026. Specifically, the Arctic Research Plan calls for research on emerging questions of (1) community resilience and health; (2) Arctic systems interactions; (3) sustainable economies and livelihoods; and (4) risk management and hazard mitigation (IARPC, 2021).

Implementing a sustained Arctic observing network will provide substantial benefits at national, regional, and local levels. For example, benefits could include increased capacity, resilience, and infrastructure in rural Alaska communities, including benefits to village economies from participation in observational activities. Sustained observations may also inform co-management councils and the ways of life and subsistence resources that Indigenous Peoples particularly depend on and that Alaska as a whole seeks to maintain. An observing network could also help inform natural resource management and climate resilience for Federal, State, and Tribal groups, while benefiting economic and national security.

3. Desired State of the U.S. Arctic Observing Network

The vision for the U.S. AON is for a comprehensive system of sustained observations and data systems that provides the basis for timely, accurate, and salient information for a broad set of stakeholders and rights holders. To achieve this vision, Arctic Indigenous and local communities must be meaningfully involved in designing and developing all stages of a sustained AON, to ensure that it is useful to them as well as to scientists and decision makers. This is best achieved by focusing on observations that are societally relevant, technically feasible, and cost-effective. For example, the Global Climate Observing System has identified 54 “Essential Climate Variables” (Appendix, Fig. B) as the foundation for climate observations that can guide appropriate mitigation and adaptation measures. Similar core variables have been identified for the ocean (Appendix, Fig. C).

Within that context, the U.S. AON should strive to support both local and global efforts, consistent with the international SAON Roadmap for Arctic Observing and Data Systems (ROADS) process (Starkweather et al., 2022), which balances Federal and non-Federal information needs under a model of societal benefit sharing that integrates across multiple scales. To achieve this desired state, the U.S. AON needs to work in unison with scientists, Indigenous Knowledge holders, and stakeholder groups at local, regional, national, and international scales.

3.1 Assessment and Justification of Recommended Observational Needs

The U.S. AON Board surveyed Federal IARPC agencies and departments to prioritize needs and gaps to address in the Arctic observing networks over the next ten years (Fig. 3). The results from this interagency survey, paired with policy drivers of national security and climate resilience, led to the following four recommendations.

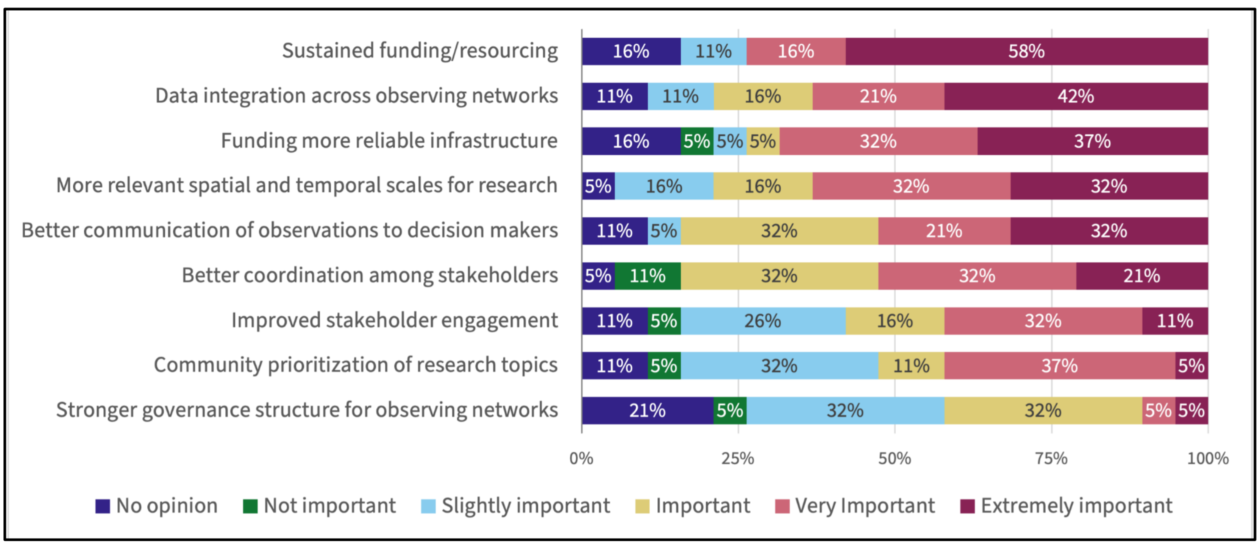

Fig. 3. Ranking by 19 Federal agencies of the most important needs for Arctic observing networks over the next ten years (n=19)

3.2 Recommendation 1: Support Coordinated and Sustained Critical Observations and Infrastructure

Long-term, sustained observations are essential to understand evolving Arctic variables over time and space and to ensure long-term planning of development, management, and security activities in the Arctic. This requires long-term commitment and funding for coordinated, critical observations. Many measurements and observations in the Arctic are funded as science and research activities. As such, funding is often committed based on the typical agency funding cycles of two to five years. While funding of observations via competitively selected proposals ensures strategic and technical updates and advancements, there is a risk that critical observations may not be sustained. Interagency collaboration on measurement requirements is needed. Satellite observations are generally longer term, but follow-on missions and measurements are not always guaranteed. Hence, it is imperative to establish an inventory of observations that need to be sustained, identify the corresponding infrastructure, and transition observations and infrastructure to long-term funding commitments. Any sustained observing infrastructure would also require logistical support to match.

3.3 Recommendation 2: Develop a Shared Data Management System Across Observing Networks to Aid Decision-Making

At present, data management systems tend to support specific subsets of Arctic observing networks and are not yet fully cross-linked nor interoperable. Much observational data are housed on project websites hosted by grantee institutions. Archives and repositories such as the Arctic Data Center, the Environmental Data Initiative, the National Snow and Ice Data Center, and the National Centers for Environmental Information are examples of where the many Arctic observing data sets can be accessed and retrieved (Appendix, Table B). A shared data management system initially built on data centers and resources must be designed and implemented to systematically enhance the usability of scientific data. Clear communication and dissemination plans are required to ensure that observational data are being measured to inform forecasting, modeling, and prediction, and other applications. The National Academies outlines best practices for open, searchable, and rapidly accessible data (NASEM, 2018), including ensuring information is Findable, Accessible, Interoperable, and Reusable (FAIR), as well as ensuring that they adhere to equitable, inclusive, and impactful principles of Collective benefit, Authority to control, Responsibility, and Ethics (CARE).

3.4 Recommendation 3: Prioritize Human and Technological Capacity Building

Human and technological capacity building will be a critical success factor for the AON, enabling a comprehensive and more societally-relevant picture of the impacts of a changing climate and empowering Tribes to expand monitoring efforts in support of their priorities and decision-making needs. Several Federal programs suggest a path forward for developing needed human capacities and building partnerships between Tribes and Federal agencies to support shared objectives in environmental monitoring (Box 1).

Box 1. Funding Opportunities to Advance Capacity for Indigenous Observations

Arctic communities are largely dependent on Federal investment for economic development. Navigating Federal processes and access to public funding is challenging to those communities. Prior to COVID-19 and the subsequent funding bills that followed, many Arctic communities were aware of climate threats, but lacked the resources to act. A May 18, 2022 Government Accountability Office report titled, “Alaska Native Issues: Federal Agencies Could Enhance Support for Native Village Efforts to Address Environmental Threat” found barriers in Federal programs, as well as a lack of coordination that limited small Alaska Native villages' access to funding. The report's recommendation was that “Congress should consider establishing a coordinating entity to assist Native villages facing environmental threats” (GAO, 2022).

Several Federal programs provide the capacity building needed to sustain long-term observations and climate resiliency in Indigenous communities. The Bureau of Indian Affairs (BIA) Tribal Climate Resilience Program enables climate preparedness and resilience while providing technical support for Federally recognized Tribes, including Alaska Natives. The Environmental Protection Agency’s (EPA) Indian Environmental General Assistance Program also offers Federally recognized Tribes and Tribal consortia with funding opportunities to plan and develop environmental protection programs, while providing the capacity needed in the long term for Tribes to observe, record, and manage subsistence variables of interest, such as caribou or muskox. More broadly, support for Indigenous- and community-led observational programs on water quality, subsistence resources, and climate resilience can also be found through the 2021 Bipartisan Infrastructure Law (BIL). BIL invests more than $13 billion directly to Tribal communities, although not all is climate-related funding. In addition, the 2022 Inflation Reduction Act (IRA) allocates $720 million in climate resilience and energy funding to Tribes.

Currently, sensor technology development, testing, and deployment has tended to be executed on a project-by-project basis for collecting specific observations. A technology development program would close the remaining temporal and spatial gaps, and aim to reduce the costs and other logistical challenges associated with Arctic observations, by developing remotely operated and autonomous systems that can geolocate and upload data in real-time or near real-time. According to a recent assessment by EU PolarNet (2021) on *in-situ* observation stations and remote observations, new technologies must be tailored to the harsh Arctic environment, with recommendations including:

- Advanced energy capabilities to include renewable sources, power generation/energy conversion, storage (e.g., battery technologies), controls/power management, and distribution (e.g., power beaming) to enable long-term autonomous operation;
- Sensor ‘ruggedization’ to cope with low temperatures, and harsh and variable conditions;
- Low cost, miniaturized technologies allowing deployment of large numbers of *in-situ* sensors;
- Automation for facilitating long-term, year-round observations in remote areas;
- Transferring to biodegradable components or developing options for instrument recovery to minimize the environmental impact; and

- Use of remotely operated devices to explore inaccessible areas or to minimize environmental impacts (e.g., aerial vehicles, gliders, rovers).

To support the parallel development of human and technological capacity, there is an underlying need to adapt existing communication technology and networks in the Arctic. Specifically, communication networks need to be accessible (i.e., affordable, scalable, and user-friendly), able to withstand harsh and variable environmental conditions, and provide high-speed bandwidth to all polar locations. In the Ocean Decade — Arctic Action Plan, the United Nations recommends "internet coverage with adequate bandwidth to provide near real time data-transfer" (UN, 2021). The Broadband Equity, Access, and Deployment Program (2022), BIL (2021), and IRA (2022) can help address the need to support network access for data transfer in rural Alaska.

3.5 Recommendation 4: Close Observational Gaps for Decision-Making on Climate Resilience and National Security

According to the European Union's PolarNet, a core challenge to providing meaningful models and scenarios to decision-makers is the wide variety of timescales at which data are collected—from the sub-second to decadal timescales—and poor spatial coverage (e.g., Fig. 1) that are often too coarse for planning to improve climate resilience and strengthen national security (EU PolarNet, 2021). Long-term, continuous data records over large geographical areas would improve models, forecasting, and predictions for hazard mitigation, resource management, and community resilience. The longstanding U.S. AON strategy, therefore, seeks to both link and expand existing research infrastructure to coordinate and integrate available environmental observations across the Arctic. US agencies and non-Federal partners support a diversity of intensive measurement programs at choice locations, supplemented by broadly distributed measurements of more easily measured parameters through repeated monitoring across marine, cryospheric, terrestrial, atmospheric, and social system domains (Fig. 4). The examples below demonstrate the breadth of collaborations that support existing observations. Additional examples of potential opportunities for observing across domains can be found in the appendix (Table E).

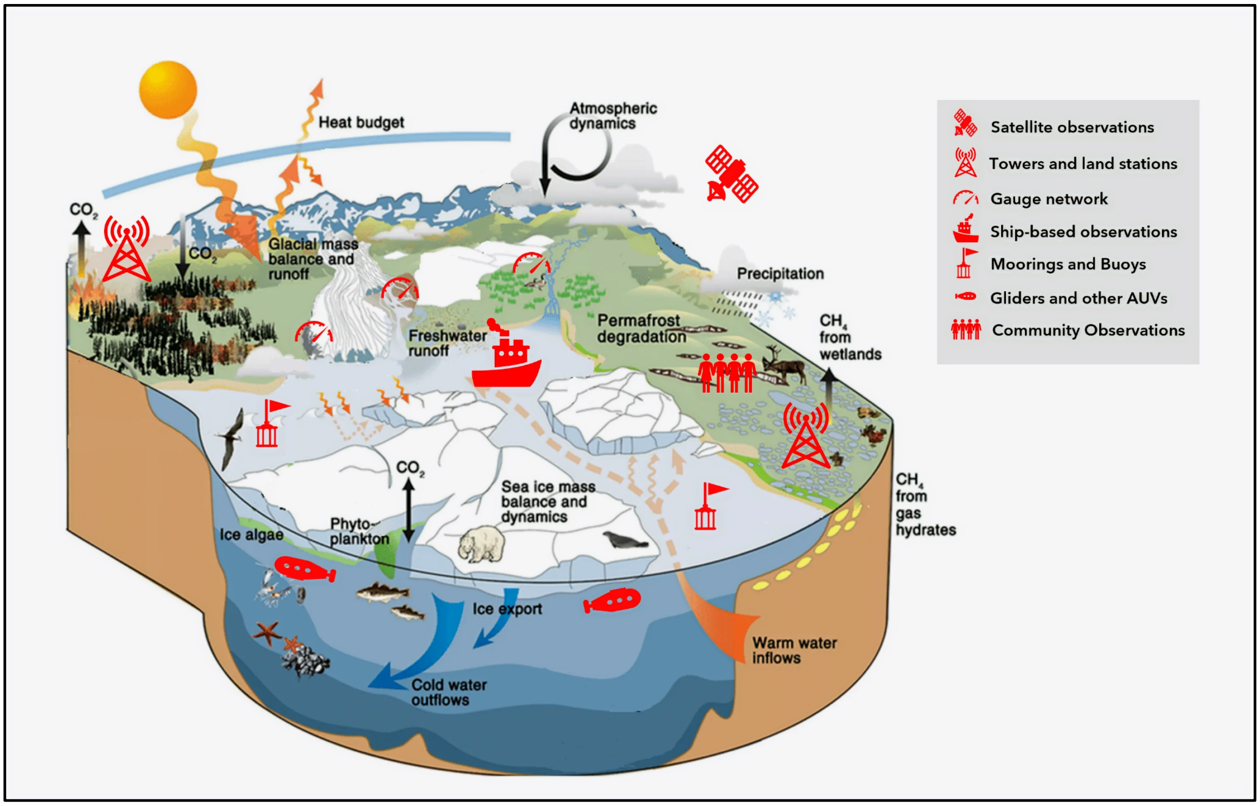

Fig. 4. The Arctic system is highly complex and tightly coupled, with strong connections to weather, climate, ecosystems, and economies across the global system. Arrows demonstrate fluxes (e.g., carbon, energy, nutrients) between aspects of the Arctic and global systems. U.S. agencies and non-Federal partners support a diversity of specialized Arctic observing systems (red icons), making integrated and coordinated planning and data dissemination imperative to support decision-makers across domains and scales (adapted from Roberts et al., 2010).

Marine and Coastal Observations: The melting of Arctic sea ice and the Greenland Ice Sheet is accelerating sea level rise, with shoreline flooding occurring in major coastal cities, including Baltimore, MD; Biloxi, MS; New York City, NY; and St. Petersburg, FL. More observations of Arctic marine and coastal processes would inform city planning and management in the lower 48. The NOAA-led Alaska Ocean Observing System (AOOS, 2021) is well-situated with its partners to support a marine and coastal observing system that is essential to providing the timely, high-resolution forecasts and information that management agencies, stakeholders, and rights holders need for immediate decision-making and long-term planning for response, mitigation, and adaptation in the region. The observing system builds on and extends the National Water Level Observation Network, the National Current Observation Program, and hydrographic observations (Office of Coastal Survey charts) that the National Ocean Service provides. Specifically, AOOS includes a network of water-level observations, coordinated harmful algal bloom and ocean acidification sampling, marine mammal monitoring, seafloor mapping, and oceanographic monitoring programs. Moored ecosystem observatories supported by NOAA and NSF make year-round biological observations and monitor the underwater soundscape. Information on marine resources, including marine mammals and fish species, is critically important for decision-making on management and subsistence harvesting by coastal communities, as well as for informing increased demand for fisheries in the Bering and Chukchi seas, and the U.S. commitment to the Central Arctic Ocean fisheries agreement. Autonomous underwater vehicles are also increasingly used for fisheries management applications and can provide near real-time data from the broad Arctic and sub-Arctic continental shelves. These marine observing systems could benefit from technological innovation for new types of observing tools and sensors to improve regional-scale models, reduce costs, and improve the understanding and delivery of information.

Cryospheric Observations: The cryosphere consists of the icy components of our climate system. For the Arctic, it includes sea ice of the Arctic Ocean, snow cover and permafrost on land, and the miles-thick ice sheet of Greenland. While changes in those components all have a significant influence on the global climate system, the changing Arctic sea ice has a tremendous impact on marine transportation, fisheries, and national security. Satellites administered by NASA, NOAA, USGS, and international organizations provide the only means for large-scale information on Arctic Sea ice, and it is imperative that those measurements are sustained. Nevertheless, specific needs and applications would require more detailed data, often information on sub-surface properties. For example, rapid warming is causing permafrost to thaw, yet the resulting greenhouse gas emissions from permafrost carbon are often under-accounted for due to major gaps in Arctic permafrost monitoring. Exemplary nationally and internationally coordinated permafrost monitoring programs, such as the Circumpolar Active Layer Monitoring program and the Global Terrestrial Network for Permafrost, provide soil temperature data at more than 125 sites over long (multi-decadal) time-scales.

Terrestrial Observations: Terrestrial observations of plant productivity, species distributions, and stream flow have important implications for carbon sequestration, food security, and watershed dynamics. Monitoring programs such as the USGS-led Federal Priority Streamgage network serves as a backbone of the greater National Streamgage Network to meet ongoing Federal priorities for freshwater data. The network was designed to meet critical information needs, such as water availability, water quality, and flood forecasting. In Arctic Alaska, there are currently 14 Federal priority streamgage locations identified, but six of them have been inactive for some years. Activated sites equipped with atmospheric and water quality monitoring sensors could improve baseline monitoring for changing Arctic conditions. Several previous synthesis reports have recognized the USGS Streamgage Network as a “high impact observation system” (OSTP, 2014; North Slope Science Initiative, 2014).

Atmospheric Observations: Atmospheric observations are critical to understanding Arctic change and the connection of a warming Arctic to global-scale impacts. While extreme events occur in the Arctic, Arctic atmospheric conditions also affect the jet stream and extreme weather throughout the mid-latitudes, including wildfires in California, flash floods in Virginia, and dangerous heat waves across the southern United States, which are becoming more frequent and severe. More atmospheric observations are needed to understand and mitigate climate change impacts. Federal agencies, including NOAA, the Department of Energy (DOE), and NSF, already support some long-term observations of atmospheric climate and composition at observatories such as the NOAA Barrow (Utqiaġvik, AK) Observatory, the DOE North Slope of Alaska observatory, and the NSF Summit Station in Greenland. These investments are leveraged through partnerships such as the International Arctic

Systems for Observing the Atmosphere (Uttal, 2016) that help coordinate atmospheric observations and data access across countries and sites. Distributed monitoring of the atmosphere is also valuable for tracking sources and impacts of aerosols and black carbon that have potential climate and health policy implications. However, even with coordination efforts specific to Arctic atmospheric observing, the number of observatories remains sparse across the Arctic. The Polar Prediction Project (PPP) was a 10-year flagship activity that began with the aim of "enabling a significant improvement in environmental prediction capabilities for the polar regions and beyond"; the Year of Polar Prediction (YOPP, 2022) was a key set of activities. PPP and YOPP used intensive observing periods coupled with model-guided studies to make optimized recommendations to improve *in-situ* observations in support of prediction, such as developing new technology to better monitor the lower atmospheric column and Arctic cloud processes. Implementing these recommendations will improve national forecasts by initializing more accurate initialization of weather models like NOAA's Unified Forecast System (NOAA SAB, 2021).

Social System Observations: The Arctic is home to Indigenous Peoples, residents of Arctic urban hubs and rural communities, and a seasonal transient workforce whose well-being is essential to support national prosperity, security, and cultural richness. Few agencies, besides the Department of Health and Human Services, perform long-term monitoring of social factors including indices of health and nutrition. Sustained observations of social factors and systems including migration patterns, food systems, communication systems, infrastructure (e.g., housing and transportation), among many others, deserve special attention, funding, and programming as integral parts of adaptation and resilience to climate change. Frameworks such as the sustainable livelihoods approach are useful for identifying what observations are needed to achieve livelihood outcomes such as improved well-being. In the sustainable livelihoods approach, external contexts (e.g., climate change, economy, governance structure, and institutions) influence how household assets (i.e., financial, physical, natural, social, and human assets) can be used to achieve livelihood outcomes through a variety of adaptation strategies (Scoones, 1998). These strategies, which deserve observation, include: migration, where risks are pooled across space; food storage, where resources are pooled over time; land (and sea) use diversification, where risks are pooled across resources; community investment, where risks are pooled across households; and market exchange, where specialization, trade, and income-generation allows for diversification. Adaptive strategies are location-specific, so social systems observations must include indicators that are Arctic-focused (e.g., AMAP, 2004; Nordic Council of Ministers, 2014, 2015). A coordinated system to collect and share information on societally relevant social system metrics, including adaptation strategies listed above, is needed to bolster capacity development in a way that is responsive to the needs of people living and working in the Arctic. Spatially disparate and irregularly collected data on human health, demographics, education, and housing makes it challenging to support progress in planning for the long-term welfare of Arctic communities.

4. Current State of the U.S. Arctic Observing Network

4.1 Characterizing Assets and Challenges for the Current Arctic Observing Network

Current observing networks provide critical and societally relevant data with modeling and predictive capabilities, yet these networks are often constrained by a lack of long-term funding, infrastructure, capacity building, and coordination (Appendix, Table C). The current distributed network is both a challenge and an opportunity to foster better cooperation and communication; no agency or country alone can fulfill the needs and requirements for this complex and fast-changing region. Although data are often available, access, integration, and usability are challenging, which constrains decision-making (IDA STPI & SAON, 2017). Current observing networks span across multiple objectives, locations, and domains (Appendix, Table D), yet they emerge from a common interest in detecting and understanding the impacts of a changing climate on Arctic systems. The following sections describe exemplary observing networks that are Indigenous- and community-led, vessel-based, autonomous platform-based, field stationed, or remote sensing. These networks leverage observational efforts while identifying important gaps and challenges that remain.

4.1.1 Indigenous- and Community-Led Observations

Indigenous- and community-led monitoring programs like the Alaska Arctic Observation and Knowledge Hub (AAOKH) and the NSF- and USGS-supported Indigenous Observing Network are exemplary for providing sustained, long-term, and holistic observations of changing environmental conditions along Alaska's coastline and waterways. The AAOKH, for example, provides year-round observations of sea ice and ocean conditions; coastal erosion; river freeze-up and break up; and coastal fish, bird, and wildlife sightings and harvest, which can provide insight into anomalous or hazardous conditions. In turn, the Indigenous Observing Network investigates changes in surface water geochemistry and active layer dynamics throughout the Yukon River Basin. Both AAOKH and the Indigenous Observing Network have the added benefit of engaging local and Indigenous people in user-based data. These Indigenous and community-led observations are largely restricted to where local people live, while other monitoring efforts like vessel-based monitoring cruises are limited temporally by sea ice. There is a need for more similar community-led observations, as well as automatic sensors on commercial boats, large ships, and aircraft.

4.1.2 Vessel-Based Observations

Vessel-based monitoring programs, such as the Distributed Biological Observatory (DBO), demonstrate how national and international funding agencies can coordinate to provide standardized ocean sampling. In the case of the DBO, the focus is on areas of high productivity and biodiversity, collecting data on seawater temperature, salinity, currents, nutrients, chlorophyll, benthic fauna and sediments, seabirds, and marine mammals. Since 2010, the DBO has been maintaining eight "hotspot" transect lines or areas of high productivity in the Bering, Chukchi, and Beaufort seas to gather long-term time series and observational data from lower to higher trophic levels. Datasets from these Arctic-going ships are critical in validating remotely-sensed data and in reducing uncertainty in key climate variables. New polar vessels, such as the Coast Guard's latest heavy icebreaker (*Sentinel*, which is scheduled to be online in 2025), are an opportunity to increase domain presence and work toward solving a long-standing issue of inadequate ship resources in the Arctic. However, there remains a general paucity of *in-situ* data, causing large spatial gaps in observations. There is also a seasonal bias in data collection with few *in-situ* observations collected during winter, and limited spatial information in Russian waters due to geopolitical tension.

4.1.3 Autonomous Platform-Based Observations

While vessel-based observations provide a breadth of data across a short period with navigable waters, autonomous platform-based monitoring uses fixed installations and autonomous uncrewed vehicles to fill gaps in those observations. Such monitoring can provide near-real-time data throughout the season, especially at times that are traditionally inaccessible due to harsh conditions, and at lower costs. Autonomous platform-based monitoring can take many shapes. For example, saildrones deployed throughout U.S. Arctic waters provide high-quality measurements of temperature, precipitation, wind speed, as well as continuous climate observations for monitoring trends. Further, uncrewed systems can be deployed as oceanographic moorings to understand the effect of shipping traffic on marine mammal distributions. Increasing the density of new technologies, such as profiling floats, gliders, and buoys, among others, can provide more data that are essential to close spatial and temporal gaps as well as reduce uncertainty in key climate trends. To support hydrographic observing systems and geospatial activities and services in the Arctic, NOAA provides foundational services, data, and tools such as water level monitoring, accurate positioning, hydrographic surveys, shoreline mapping, and nautical charts in support of safe maritime transportation and economic growth. NOAA operates and maintains real-time observation networks such as: the Continuously Operating Reference Stations which provides three-dimensional positioning for many observations, while also generating nautical charts and topographic maps; the National Water Level Observation Network, which provides water level data for hydrographic surveys that update nautical charts as well as authoritative sea level trends, tide predictions, and storm surge data; and AOOS high-frequency radars for ocean mapping in the Arctic. These autonomous systems are critical to fully map U.S. Arctic coastal waters, as vessel-based hydrographic surveys would require over 100 years of continuous ship-time. Despite such an apparent wealth of information on shorelines, hydrographic, and positioning observation systems, only 80 percent of U.S. Arctic waters are mapped.

4.1.4 Field Station Observations

Long-term datasets from field stations provide critical insights on changes in atmospheric composition, aerosols, clouds, and surface radiation. Data from these observatories help validate satellite observations, improve models, and support process studies, and yet only a handful of observatories are operating in the Arctic. These field stations include one in the North Slope of Alaska supported by NSF; two in Utqiaġvik supported by NOAA and DOE; and one in Summit, Greenland, owned and operated by NSF with operational support provided by a prime contractor. More baseline observatories for long-term monitoring in the Arctic would give a better picture of the complexity of the region.

4.1.5 Satellite and Airborne Observations

Large-scale and long-term monitoring in the Arctic would also not be possible without the important satellite and airborne missions critical to Arctic research operated by NASA, NOAA, and other agencies. For example, more than 40 years of satellite passive microwave measurements provide the only means for Arctic-wide mapping and monitoring of sea ice. The Gravity Recovery and Climate Experiment (GRACE and GRACE-FO) satellites, a joint venture between NASA and the German Research Centre for Geosciences, has been measuring changes in ice sheet mass, oceanography, and terrestrial water storages including groundwater that are important to predicting sea level rise. Altimetry over land and sea ice that measures changes in thickness are available through ICESat-2 and Cryosat-2. NOAA satellite missions and the Joint Polar Satellite System make weather and key climate information readily available. The USGS Landsat series provides necessary information for emergency response and disaster relief, regional and resource planning, change detection analysis, and education. Potential gaps are inevitably associated with interruptions in long-term observational time series due to sensor failure. More synthetic aperture radar satellite data can also help improve sea ice extent datasets in the near future. As for airborne campaigns that apply to Arctic environmental change, government agencies and partners operate nearly 60 research aircraft. Examples include the Arctic Boreal Vulnerability Experiment and the carbon dioxide and methane airborne campaigns led by NASA and the German Aerospace Center. Remotely-sensed data along with *in-situ* and other sustained observations across scales help reduce uncertainty, improve models, and contribute to our understanding of trends.

4.2 AON Coordination and Engagement

Currently, coordination of Arctic observations in the United States happens through several interagency bodies, including IARPC and U.S. AON (Appendix, Fig. A), as well as through platform-centric bodies such as the U.S. Interagency Arctic Buoy Program and University-National Oceanographic Laboratory System Arctic Icebreaker Coordinating Committee. These bodies' primary goal is to support national decision-making in Arctic observing priorities, research, and policy collaboration. Further, there are a number of research coordination bodies whose main audience is academic researchers, including the Arctic Research Consortium of the United States, IARPC, and SEARCH. IARPC links Federal-led efforts to researcher-led efforts through the web platform IARPC Collaborations. Nonetheless, communication between Federally-led bodies could be improved to ensure a whole-of-government approach to U.S. Arctic observations.

In the context of Arctic research and observations, non-Federal organizations are important partners with agencies. These organizations are often Alaska- or Arctic-based and integrated within communities, and are thus more responsive to local needs. Example organizations include agencies within the State of Alaska (Department of Environmental Conservation, Department of Natural Resources, Department of Fish and Game, and others), independent research organizations (North Pacific Research Board, Alaska Ocean Observing System), academic projects (AAOKH), and Indigenous organizations (Eskimo Walrus Commission, and other co-management boards, Tribal nonprofits, and Tribal councils).

4.3 Current Data Management: Accessibility and Uses

With an array of current Arctic observing systems, data, and programs (Appendix, Table B), several challenges emerge due to the lack of data management infrastructure to integrate data from these specialized platforms and instruments. At the moment, a common portal or database that cross-links existing repositories for key datasets to assist data discovery is limited. For example, there is currently one online portal, the Arctic Observing Viewer that helps with visualization, strategic assessment, and decision support for initiatives tied to Arctic observing. The Arctic Observing Viewer displays observing sites and is primarily for policy makers, science planners, and data management specialists to better plan, coordinate, and achieve monitoring objectives. Concerns with data sovereignty, lack of resourcing, and governance issues are constraints toward making such an integrated system a reality. Free and open data sharing practices and partnerships among Federal agencies, regional entities, State of Alaska, and Indigenous and community-led observing networks are also lacking and are critical to filling gaps in the production and access to data. Another major challenge in Arctic data management is data latency and the need for real-time to near-real-time data analysis systems. This delay can be due to poor telecommunications and power infrastructure, publication embargoes, delays in processing, and/or lack of incentives to make data readily available. Interoperability also remains a challenge while human subjects data and Indigenous Knowledge require special tagging and processing due to data ownership concerns, data ethics, and privacy.

The value of data also depends on the consistency of datasets collected by different groups and in different regions. Data standards are being widely used, though not uniformly applied. The scientific community plays an important role in this process. For example, the NSF Research Coordination Networks program “supports networks that foster communication and new collaborations among scientists, engineers and educators who share a common interest in a new or developing area of science or engineering." One area of interest for many is to encourage research coordination networks to develop community standards for data and metadata. Funding mechanisms, like research coordination networks, provide much-needed human capacity to work across diverse data landscapes. Another example is NOAA’s merged data files, which combine meta-data with data for observers and modelers. Through the overlap of model and observation merged data files, researchers and data managers can increase data uptake and enable data comparison. To help coordinate observing metadata for the polar science community, the Polar Observing Assets Working Group was established in 2020 under the SAON Committee on Observations and Networks. The working group provides technical guidance for sharing information about observing activities, promotes best practices for interoperability beyond the dataset level, and creates recommendations for the adoption and implementation of established standards and solutions.

Lastly, having access to data does not necessarily ensure that data will provide the intended societal benefit if there are challenges to their usability. Key tools to easily discover, parse, download, visualize, or assimilate data into key products and services are necessary. Some examples of initiatives to help tackle this challenge include data catalogs by NOAA’s PolarWatch, AOOS’ data portal, and NSF’s Arctic Data Center. Initiatives such as the NOAA-developed Environmental Research Division’s Data Access Program also give a simple, consistent way to download subsets of scientific data in common file formats and to make graphs and maps. With the massive amounts of data openly available now to end-users, it is imperative to use cutting-edge technology, such as artificial intelligence and machine learning, to quickly make sense of the data. It is also important to consider possible future datasets that will be collected with methods and technologies that do not yet exist.

5. Toward an Implementation Plan for a Sustained U.S. Arctic Observing Network

A strategic and inclusive path forward through an Implementation Plan is needed to move a sustained U.S. AON forward, engaging the combined efforts of Federal and non-Federal partners who support and benefit from the U.S. AON. Such an Implementation Plan should include a comprehensive synthesis of existing activities; a policy-driven needs assessment; a rigorous set of requirements for observing and data systems derived from that assessment; and an outline of agency responsibilities for coordination, governance, logistical support, and management. A central challenge here is generating the collective focus and engagement needed to align diverse missions and goals.

5.1 Guiding Principles for Driving the Decision-Making Process

Recent national and international efforts have focused on collectively developing the needed planning principles and tools to support decision-making for the AON. Nationally, the U.S. AON Board has advanced planning strategies focused on societal benefits and promoted the use of these approaches with their international partners (IDA STPI & SAON, 2016). The Circumpolar Biodiversity Monitoring Program has spent years developing its Focal Ecosystem Components (e.g., CAFF, 2021) to identify which parameters of the ecosystem need to be monitored to meet the mission of safeguarding Arctic biodiversity. Its counterpart, the Arctic Monitoring and Assessment Program has done the same for contaminants and climate variables (AMAP, 2021). International efforts like the SAON facilitate partnerships around the full range of monitoring needs across the local, regional, and global levels.

Interagency efforts and those led by Indigenous organizations have also provided enhanced guidance on equitable engagement with Indigenous communities, such as the Principles for Conducting Research in the Arctic (IARPC, 2018) and the Protocols for Equitable and Ethical Engagement (ICC, 2022). Many of these planning and mobilization efforts are just entering their demonstration phase, but important planning principles common to these efforts are emerging and are recommended for the development of a U.S. AON Implementation Plan, as well. They include: creating an inclusive and transparent planning process framed around broadly shared benefits; aligning efforts across international partners in ally Arctic and non-Arctic states; implementing FAIR and CARE principles for data management; and including technology, capacity, and infrastructure development in implementation plans.

5.2 How U.S. AON Can Support Next Steps

The Federal U.S. AON Board sits at the center of national AON planning efforts. The broader U.S. AON initiative includes a collection of Federal and non-Federal activities at the interface between observing technology and policy issues. The U.S. AON Board engages with and receives input from non-Federal partners, including Arctic Indigenous Peoples and non-Indigenous Arctic residents, through IARPC Collaborations. In 2019, the U.S. AON Board conducted a visioning exercise to focus its efforts. In response to this visioning exercise, U.S. AON began developing decision-support tools organized around societal benefits to identify gaps within current observing systems and needed actions to improve networked observations. These benefit analysis tools were derived from those used by other

Federal groups, including the U.S. Group on Earth Observations. Nationally recognized approaches should continue to shape the U.S. AON Implementation Plan; these approaches include the SAON ROADS process, as well as observing system recommendations generated under efforts by Arctic Council Working Groups.

Despite such a groundswell of action, sustained progress on AON planning and implementation requires substantial capacity. A strong analogue for such capacity is provided by the ongoing example of coordinated interagency and international efforts to improve ocean observing capabilities (Box 2), which includes centralized national leadership, interagency collaboration, regional capacities, and robust non-Federal partnerships.

Box 2. Exploring Ocean Observation Networks as a Model for AON

The Interagency Ocean Observation Committee (IOOC) was chartered by OSTP's Subcommittee on Ocean Science and Technology in 2009. The Integrated Ocean Observing System (IOOS), governed by IOOC, consists of 11 regional associations. It is a coordinated national and international network of ocean observations with associated data transmission, modeling, and analyses providing key information to scientists, state and Federal decision makers, Indigenous communities, and the general public. The U.S. IOOS is the United States' major contribution to the United Nations (UN) Global Ocean Observing System (GOOS). The UN GOOS provides state-of-the-art information about the state of the ocean (including living resources), supports continuous forecasts of the future conditions of the ocean, and furnishes the basis for climate change assessments and present and future scenarios (Sandven et al., 2005).

The Alaska Ocean Observing System (AOOS) is one of the 11 Regional Associations in the United States. The oceanic data collected by AOOS are available in real-time, near-real-time, or retrospectively. Easier and better access to this information is improving our ability to understand and predict coastal events such as storms, sea ice changes, wave heights, sea level changes, and marine and coastal ecosystem changes, which give insight into climate changes, anthropogenic pollution, extreme weather events, overfishing, and periodic erosion episodes. Such ocean observing systems should be enhanced in the U.S. Arctic to match the capabilities found in the lower 48 states, and these planning processes should be replicated more broadly beyond the oceans to an integrated, sustained, and coordinated AON.

5.3 Indigenous Engagement Activities and Models

Any Federally developed Implementation Plan for AON, including its design, must include meaningful and robust consultation and engagement with Indigenous Peoples (AOS EOC, 2018; ICC, 2021). Meaningful Indigenous engagement means consultation and involvement in the formation, writing, and execution of the Implementation Plan by ensuring capacity for Indigenous Peoples to engage. The Northern Bering Sea Climate Resilience Area, established by Executive Order 13754 in 2016, and reinstated by President Biden in 2021, provides an example of Indigenous values informing policy. This effort provides a model for bridging the different value systems from Indigenous Knowledge and academic science through a framework that includes a Federal task force and Bering Intergovernmental Tribal Advisory Council. Indeed, Indigenous Knowledge was formally recognized in a 2021 White House memorandum as "one of the many important bodies of knowledge that contribute to the scientific, technical, social, and economic advancements of the United States and to our collective understanding of the natural world." A co-production of knowledge approach, using science and Indigenous Knowledge, will be essential for developing adaptation policies and practices for climate resilience and sustainability (Johnson et al., 2020; Daniel & Behe, 2017). This and other Federal programs can serve as a model for advancing planning and implementation for the AON in partnership with Arctic Indigenous Peoples.

5.4 International Models of Successful Arctic Observing Networks

International cooperation is essential to achieving national goals within the vast Arctic region, shared by eight Arctic nations. There is a long tradition of scientific cooperation in the region, anchored around major initiatives like International Polar and Geophysical Years. The Arctic Council is one high-level intergovernmental forum that provides a mechanism to address the common concerns and challenges faced by Arctic peoples and governments. In 2004, two working groups, Conservation of Flora and Fauna (CAFF) and Arctic Monitoring and Assessment Program (AMAP), together with the International Arctic Science Committee (IASC) developed follow-up strategies to fill in observational gaps across the Arctic across the marine, coastal, freshwater, and terrestrial ecosystems. Exemplary keystone programs such as CAFF's Circumpolar Biodiversity Monitoring Program work to standardize, coordinate, and enhance existing Arctic monitoring efforts by collecting and harmonizing relevant biodiversity data, to allow for a deeper understanding of significant trends (CAFF, 2021). Much of the work of the Arctic Council that involved Russia, however, has been on pause since Russia's illegal and unjustified invasion of Ukraine.

The Arctic Council and IASC jointly initiated SAON in 2011 to address the persistent shortcomings in sustaining and coordinating Arctic observations that are maintained by its many national and organizational partners. The United States has served on the SAON Board since its inception in 2011, and U.S. AON was created to support SAON's work as the U.S. national committee. SAON's ROADS process provides a systematic planning mechanism to develop and link observing and data system requirements and implementation strategies in the Arctic region. ROADS is both a comprehensive concept, building from a societal benefit assessment approach, and one that can proceed step-wise so that the most imperative Arctic observations—referred to as shared Arctic variables—can be rapidly improved. The success of the ROADS process will ultimately be measured by its success in realizing concrete international investments in well-structured partnerships for the improved sustainment of Arctic observing and data systems in support of societal benefits.

Allied Arctic and non-Arctic nations engage in a range of activities that support the international AON. For example, the European Commission's Horizon 2020 Integrated Arctic Observation System (INTAROS) project (2017-2021; Pirazzini et al., 2020) took action to enhance existing networks, with a particular focus on improving services through the EU Earth observation program, Copernicus. The follow-on to INTAROS, Arctic PASSION (Pan-Arctic System of Systems) (2021-2025) will employ the planning tools of the SAON ROADS process to identify specific needed improvements to the European AON and improve public services related to things like shipping, infrastructure/permafrost interactions, and wildfire management. No single agency, region, or country can fulfill the needs and requirements of this complex and fast-changing region; coordination and collaboration will be required.

6. Summary, Recommendations, and Next Steps

Congress has recognized that Arctic observing and data systems underpin our understanding of the complex Arctic system and its role in the global system. The magnitude, pace, and extent of climate-driven changes in the Arctic require timely and relevant information to support decision-making across scales. The United States' current capabilities are not meeting this urgent challenge. U.S. AON is recommended to mobilize efforts across U.S. agencies to address this. U.S. AON should implement the SAON ROADS process to establish an international network of sustained and integrated observations over the next ten years. The Integrated Ocean Observing System (IOOS) program provides inspiration and serves as a model for catalyzing individual agency efforts into unified progress in support of decision-making needs. Specifically, the recommendations of this report for U.S. Arctic observing networks are to:

1. Support coordinated sustained critical observations and infrastructure.
2. Develop a shared data management system across observing networks that enables cross-agency data synthesis and rapid dissemination of data in formats required by decision makers.
3. Prioritize human and technological capacity building.
4. Close observational gaps in marine, cryospheric, terrestrial, atmospheric, and social systems observations using the best available human and autonomous observations.
5. Ensure engagement and inclusion of stakeholders and rights holders, including Indigenous Arctic residents, to extend the benefits beyond scientists and government agencies to those living in the Arctic.

Next Steps: This report recommends that the U.S. AON Board initiate an interagency Implementation Plan to mobilize the development of a sustained, coordinated Arctic Observing Network. That process can commence during monthly U.S. AON Board meetings, with events like the annual Arctic Science Summit Week and the biennial Arctic Observing Summit serving as flashpoints for moving the agenda forward. NSF, NOAA, and NASA will lead interagency efforts to reach consensus and identify priorities for critical observations. Current U.S. Arctic policy provides a high-level framework for developing the requirements for AON priority actions. Implementation Plan development should allow sufficient time for meaningful engagement from Federal and state agencies, academic and non-governmental organizations, industry, and Indigenous Peoples including Tribal governments and Indigenous organizations.

7. Acronyms

AAOKH	Alaska Arctic Observatory and Knowledge Hub
AMAP	Arctic Monitoring and Assessment Program
AON	Arctic Observing Network
AOOS	Alaska Ocean Observing System
ARPA	Arctic Research and Policy Act (1984)
BIA	Bureau of Indian Affairs (Department of the Interior)
BIL	Bipartisan Infrastructure Law (2021)
BOEM	Bureau of Ocean Energy Management (Department of the Interior)
CAFF	Conservation of Arctic Flora and Fauna
CARE	Collective benefit, Authority to control, Responsibility, and Ethics
CLEO	Circumpolar Local Environmental Observer
DBO	Distributed Biological Observatory
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
EcoFOCI	Ecosystems and Fisheries-Oceanography Coordinated Investigations
EPA	Environmental Protection Agency
EU	European Union
FAIR	Findable, Accessible, Interoperable, and Reusable
GAO	Government Accountability Office
GOOS	Global Ocean Observing System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
HUD	U.S. Department of Housing and Urban Development
IARPC	Interagency Arctic Research Policy Committee
IASC	International Arctic Science Committee
ICC	Inuit Circumpolar Council

INTAROS	Integrated Arctic Observation System
IOOS	Integrated Ocean Observing System
IRA	Inflation Reduction Act (2022)
LEO	Local Environmental Observer
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service (Department of the Interior)
NRC	National Research Council
NSAR	National Strategy for the Arctic Region
NSF	National Science Foundation
NSTC	National Science and Technology Council
OSTP	Office of Science and Technology Policy
PASSION	Pan-Arctic System of Systems
PPP	Polar Prediction Project
SAON	Sustaining Arctic Observing Networks
SAON ROADS	SAON Roadmap for Arctic Observing and Data Systems
SEARCH	Study of Environmental Arctic Change
STPI	Science and Technology Policy Institute
U.S. AON	United States Arctic Observing Network
USGS	U.S. Geological Survey (Department of the Interior)
YOPP	Year of Polar Prediction

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9. Appendix

Fig. A. Examples of national and international observing networks organized by and for researchers or government agencies. *Note: Not all organizations are represented here.*

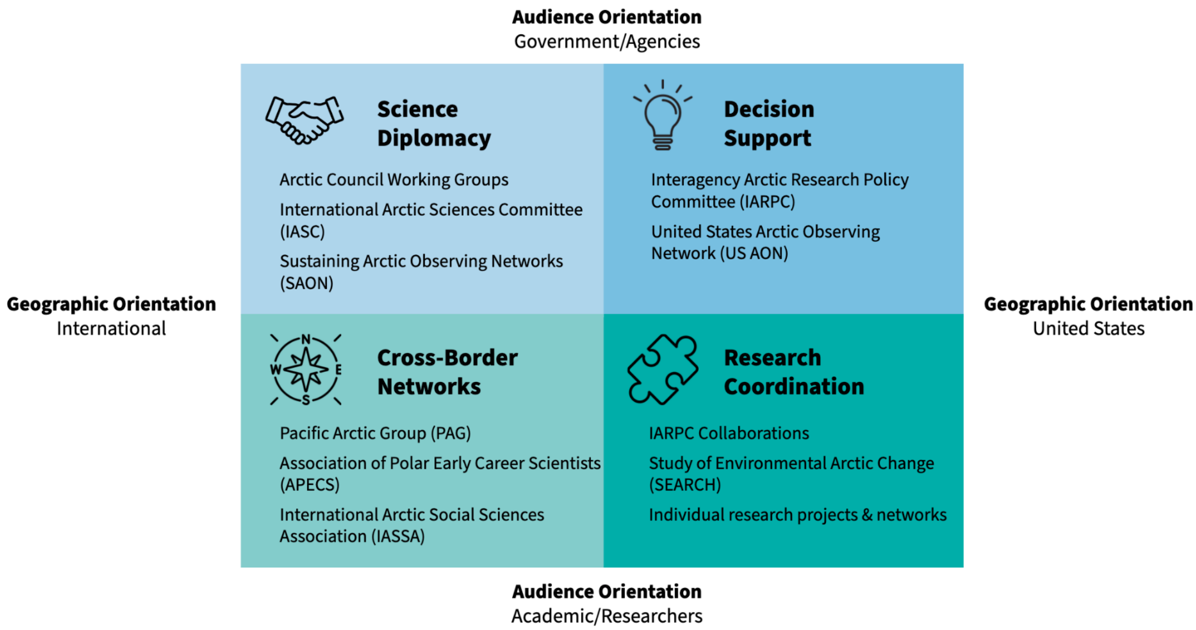

Fig. B. The Global Climate Observing System's Essential Climate Variables (ECV)

Atmosphere		
Surface	**Upper Air**	**Atmospheric Composition**
Precipitation	Earth radiation budget	Aerosols
Pressure	Lightning	Greenhouse gases
Radiation budget	Temperature	Clouds
Temperature	Water vapor	Ozone
Water vapor	Wind speed and direction	Precursors for aerosols & ozone
Wind speed and direction		

Land			
Hydrosphere	**Cryosphere**	**Biosphere**	**Anthroposphere**
Groundwater	Glaciers	Above-ground biomass	Anthropogenic water use
Lakes	Ice sheets and shelves	Albedo	Anthropogenic greenhouse gas fluxes
River discharge	Permafrost	Evaporation from land	
	Snow	Fire	
		Fraction of absorbed photosynthetically active radiation (FAPAR)	
		Land cover	
		Land surface temperature	
		Leaf area index	
		Soil carbon	
		Soil moisture	

Ocean		
Physical	**Biogeochemical**	**Biological/ecosystems**
Ocean surface heat flux	Inorganic carbon	Marine habitats
Sea ice	Nitrous oxide	Plankton
Sea level	Nutrients	
Sea state	Ocean color	
Sea surface currents	Oxygen	
Sea surface salinity	Transient tracers	
Sea surface stress		
Sea surface temperature		
Subsurface currents		
Subsurface salinity		
Subsurface temperature		

Fig. C. Integrated Ocean Observing System (IOOS) Core Variables

IOOS CORE VARIABLES The 34 1008 Core Variables: Ocean observing measurements required to detect and predict changes in the ocean		
Physics	**Biogeochemistry**	**Biology and Ecosystems**
Bathymetry	Acidity	Biological vital rates
Bottom character	Colored dissolved organic matter	Coral species & abundance
Currents	Contaminants	Fish species & abundance
Heat flux	Dissolved nutrients	Invertebrate species & abundance
Ice distribution	Dissolved oxygen	Marine mammal species & abundance
Salinity	Ocean color	Microbial species, abundance, & activity
Sea level	Optical properties	Nekton diet
Surface waves	Pathogens	Phytoplankton species & abundance
Stream flow	Partial pressures of CO2	Seabirds species & abundance
Temperature	Total suspended matter	Sea turtles species & abundance
Wind speed & direction		Submerged aquatic vegetation species & abundance
		Sound
		Zooplankton species & abundance

Table A. Current U.S. AON Board Agency Representatives

Department or Agency Name
National Oceanic and Atmospheric Administration (NOAA)—Co-Chair
National Science Foundation (NSF)—Co-Chair
National Aeronautics and Space Administration (NASA)—Co-Chair
Department of Energy (DOE)
Environmental Protection Agency (EPA)
Department of Defense (DOD)
Department of Housing and Urban Development (HUD)
Department of Interior (DOI) Bureau of Ocean Energy Management (BOEM)
Department of Interior (DOI) US Geological Survey (USGS)
Department of Interior (DOI) National Park Service (NPS)
Department of State (DOS)
Interagency Arctic Research Policy Committee (IARPC)
Office of Science and Technology Policy (OSTP)

Table B. Dispersed data curation and distribution services

Dept/Agency	Data Center
DOE	Atmospheric Radiation Measurement; Next-Generation Ecosystem Experiments
DOI (USGS)	Earth Resources Observation Systems Data Center
NASA	Earth Observing System Data and Information System
NOAA	National Centers for Environmental Information; Alaska Ocean Observing System
NSF	Arctic Data Center; Exchange for Local Observations and Knowledge

Table C. Research, organizational, and uptake challenges to Arctic observing networks

Type	Challenge	Description
Research	Physical challenges	Arctic conditions such as polar night, extreme cold, lack of infrastructure, and communications systems increase observing costs, constrain coverage, and limit real-time data dissemination (Starkweather et al., 2022).
	Temporal mismatches	The variety of time-scales—from sub-second to millennial—is a challenge for observational modeling and often provides information at time-scales too coarse for decision makers (NASEM, 2018).
	In-situ and satellite observations	Gaps of *in-situ* and satellite data in the Arctic remain, which requires considerable human and financial resources to address (Pirazzini et al., 2022). There is also a seasonal bias in the data being collected, with a huge majority of data being gathered during boreal summers.
	Lack of long-term funding	Multiyear, sustained funding is rare, which is a challenge for long-term data collection, preservation and maintenance. Additional uncertainty in agency budgets complicates planning for infrastructure, staffing, data collection, and other agency goals, but particularly affects local and community-led observational networks (Johnson et al., 2015).
	Funding values	Federal funding, process, and prioritization often reflects a biological-physical science research bias, valuing some knowledge systems over others, which constrains community-developed and Indigenous research priorities (Inuit Tapiriit Kanatami, 2018).

Type	Challenge	Description
Organizational	Lack of planning governance	There is currently no mechanism for supporting broad decision-making across the scope of the AON, either nationally or internationally. U.S. Arctic observing is funded across multiple agencies, but no single agency is the lead, which complicates strategic planning. The SAON ROADS process was created for shared planning tools and governance but it is still only in a pilot phase.
	Lack of data standardization	A lack of standardized protocols and data standards such as quality assurance and quality control across disciplines inhibits data integration and decision-making (Lee et al., 2019).
	Data sovereignty	A potential challenge is to ensure that data collected adheres to potential restrictions by the communities with regard to data use (ICC Alaska, 2020; Hauser et al., 2021).
Uptake	Data accessibility and usability	Data are often available, but discovery, access, and usability are challenging, which constrains management decisions or stated results of scientific research (IDA STPI & SAON, 2017).
	Lack of communication infrastructure	High-speed, high-quality 4G and/or 5G communication infrastructures are necessary for most science, yet internet speed is considerably slower in higher latitudes than in lower latitudes of Arctic nations because of infrastructural inequities (IDA STPI & SAON, 2017; Inuit Tapiriit Kanatami, 2018; UN, 2021).

Table D. Current examples of Arctic surface observing assets by domain and theme

Domain	Theme	Description of existing observing networks
Atmosphere	Arctic amplification	DOE's Atmospheric Radiation Measurement provides measurements from the North Slope of Alaska observatory with comprehensive data about atmospheric, cloud, and radiative processes.
	Atmospheric circulation	NOAA Earth System Research Laboratories operates staffed atmospheric baseline observatories from which numerous *in-situ,* remote atmospheric, and solar measurements are conducted, including one in Utqiaġvik. Their efforts support global observation and research on the atmospheric constituents that drive climate change, stratospheric ozone depletion, and baseline air quality.
Cryosphere	Ice sheet hydrology	NASA and the German Aerospace Center's Gravity Recovery and Climate Experiment (GRACE) project flies twin spacecraft in tandem around Earth to study key changes in the planet's waters, ice sheets and the solid Earth.
	Permafrost	DOE's Next-Generation Ecosystems Experiments is a 10-year project (2012-2022) to improve our predictive understanding of carbon-rich Arctic system processes and feedbacks to climate.
Marine	Biodiversity	Arctic Marine Biodiversity Observing Network is a demonstration project to build an operational marine biodiversity observing network from microbes to whales, located on the Chukchi Sea continental shelf in the United States.

	Net primary production	NOAA's EcoFOCI has long-term moorings, drifters, and shipboard measurements to improve understanding of ecosystem dynamics and to inform management of living marine resources.
	Ocean acidification	NOAA's Alaska Ocean Acidification Network provides relevant information, works with scientists and stakeholders to identify knowledge gaps and needs, shares best practices, and acts as a resource hub of ocean acidification information.
	Marine mammals	National Marine Fisheries Service marine mammal surveys provide information on population trends, productivity rates, estimates of human-caused mortality, and other sources of serious injury.
	Sea ice regimes	AAOKH supports local observing in coastal regions, weaving connections between Indigenous and scientific communities.
Terrestrial	Pollutants	The Arctic Council's Arctic Contaminants Action Program four expert groups (Persistent Organic Pollutants and Mercury, Waste, Indigenous Peoples' Contaminant Action Program, and Short-lived Climate Pollutants) work to develop actions to reduce pollution in the Arctic.
	Hydrology	USGS's Streamflow Data provides daily streamflow data for Alaska, recorded at 15- and 16-minute intervals at measure stations.

	Biodiversity	USGS's North Pacific Pelagic Seabird database includes more than 460,000 survey transects that were designed and constructed by numerous partners. Additionally, the NPS Arctic Network Vital Signs monitoring program includes information on key species of subsistence interest including caribou, Dall's sheep, and muskox.
Societal	Human health	The Arctic Council's Arctic Monitoring and Assessment Program (AMAP) conducts and publishes an annual human health assessment as part of its mandate to monitor and assess the changes in the Arctic.
	Food security	Indigenous Sentinels Network (Bering Watch) provides remote, Indigenous communities with tools, training, networking and convening, coordination, and capacity for ecological, environmental, and climate monitoring. It includes monitoring of salmon and other species of importance to Yukon River communities in interior Alaska.

Table E. Additional examples of potential opportunities for sustained Arctic observing

Observation	Description
Benchmark glaciers	Since the late 1950s, USGS scientists have maintained a glacier mass-balance measurement program in North America that now covers five glaciers (Gulkana, Lemon Creek, South Cascade, Sperry, Wolverine) using both field and remote sensing techniques. They measure snow accumulation and snow and ice melt at specific locations on the glaciers, then extrapolate those point observations across the entire glacier surface. They also measure air temperature and precipitation at each site to connect glaciers and climate change. The benchmark glacier project could be strategically expanded to include McCall Glacier in the Brooks Range. McCall is the only glacier in the U.S. Arctic with a glaciological record of several decades. It was studied during the International Geophysical Year in 1957-58, and from 1969 to 1975 as a contribution to the International Hydrological Decade, but sustained observations have been sporadic since then because of inconsistent or inadequate funding.
Ice sheets	The Greenland Ice Sheet is the largest single contributor to rising global sea levels, and monitoring the ice sheet and its many outlet glaciers is critical to understanding how the ice sheet is responding to a warming climate. Numerous Federal agencies, including NSF and NASA, support researchers taking observations of ice sheet processes both on the ground (NSF) and from airborne/satellite observations (NASA/NOAA). Current ice sheet modeling efforts are bolstered both by *in-situ* observations of small-scale ice sheet processes at individual glaciers or locations on the ice sheet, as well as observations taken by satellites that resolve larger-scale phenomena occurring across the entire ice sheet. Continued, sustained observations and measurements of ice sheet processes could help constrain the uncertainty in the ice sheet models that are a critical component in determining sea level rise projections.
Vegetation mapping	Comprehensive vegetation mapping and monitoring products help inform land-use planning and natural resource management in Alaska. Currently, statewide vegetation mapping and monitoring falls between agency responsibilities, so a working group consisting of Federal, State, academic, and private entities have developed standards for statewide vegetation mapping and monitoring.

Biodiversity	Having and maintaining high biodiversity is important for a number of reasons, including community resilience to climate change. The Arctic, however, has lower baseline biodiversity to begin with due to its lower primary productivity. Improved monitoring of biodiversity across multiple ecosystems through core variables identified as Focal Ecosystem Components, where changes in status likely indicates changes in the overall environment, could improve the tie between monitoring and management decisions (CAFF, 2021). The list of potential Focal Ecosystem Components can be developed based on expert scientific and Indigenous Knowledge, community needs, and conceptual models, and can be applied across multiple ecosystems to support observations across multiple networks. Biodiversity can have major implications across scale, yet observations for terrestrial animal biodiversity are largely restricted to a single site that cannot be extrapolated across scale. Subsistence-focused biodiversity monitoring takes place every year in Alaska by the Alaska Department of Fish and Game, USGS, the U.S. Fish and Wildlife Service, NPS, BOEM, the Bureau of Land Management, and NOAA. However, better visibility and usability could be helpful for such biodiversity monitoring.
Sea ice	Sea ice plays a critical role in the Earth system by both reflecting solar radiation and regulating the transfer of heat and energy between the atmosphere and the ocean. Shrinking Arctic sea ice cover has been observed and documented by Federally funded research scientists since the beginning of the satellite record, and *in-situ* observations of sea ice conditions remain a critical piece in monitoring small-scale processes that are not resolved by satellite data alone. The recent MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) expedition was an international scientific endeavor. It was focused on a year-long (September 2019 through October 2020) operation of an icebreaker equipped as a scientific vessel taking on-board measurements (as well as supporting a network of on-ice field measurements) as it drifted with the sea ice through the western Arctic Ocean. This expedition was an acknowledgement by the global scientific community that sustained, interseasonal observations/measurements of sea ice and the polar ocean system are necessary for enhanced understanding of the radiative balance between the ocean and the atmosphere, as well as gathering critical information about sea ice conditions as they impact geopolitics and national security interests in the Arctic.

Remote geophysical	Beginning in 2017, an unprecedented sensor network was created across Alaska under the NSF-sponsored USArray program. Sensor platforms blanketed Alaska in a grid-like pattern, providing the first real-time observations in many areas of the U.S. Arctic. The data are unique because they are purposefully located far from communities; they are evenly distributed across the region; they blend traditional meteorological and soil temperature observations with infrasound and seismic records, allowing for novel cross-disciplinary observations of environmental change; and data are sampled every second and served primarily through direct-to-satellite communications. Forty-five of these sites in the ARPA-defined Arctic have been adopted for long-term operation. The NSF AON program has provided partial financial support into 2025 with the stated hope of catalyzing and expanding a long-term capability. NOAA's National Mesonet Program has provided modest seed funding on a year-by-year basis. The Defense Threat Reduction Agency has seeded a pilot project through 2023 to strengthen the infrasound effort. Current expansion efforts are focused on increasing the footprint of the soil temperature capabilities and adding Global Navigation Satellite System capabilities to track atmospheric water content and high-latitude space weather, to provide enhanced survey capabilities. Despite the uniqueness of USArray, the effort does not have a long-term plan. Because of the diversity of observations, long-term planning for the network should be governed through formal interagency processes.
Community -driven monitoring	Several local examples demonstrate the utility and benefit of including community residents to provide cost effective monitoring of observed status and trends in local flora and fauna, as well as broader landscape level changes. For example, the Local Environmental Observer (LEO) Network started as a grassroots Alaska movement by the Alaska Native Tribal Health Consortium with funds from EPA in 2009. The Alaska Native Tribal Health Consortium, in consultation with Tribal leadership and environmental staff, developed a tool to document and share environmental observations recognizing the value of Indigenous Knowledge and local knowledge. The web-based platform is a network of people, local observers, and topic experts who share knowledge about unusual events involving animal, environmental, and weather occurrences. The LEO Network has grown to over 3,000 members, is open for participation by anyone, and encourages inclusion of Indigenous Knowledge. It has recently expanded into a Circumpolar Local Environmental Observer (CLEO) Network to be used by and to benefit communities across the Arctic. With dedicated

	funding, the CLEO Network could be harnessed to more fully monitor conditions of food security and food web vitality. For example, a study by USGS, the U.S. Fish and Wildlife Service, Alaska Department of Fish and Game, and the Polar Science Center found that monitoring both the annual availability of sea ice and the status of prey populations through the sampling of subsistence harvested ice seals could yield a more thorough indication of the status of polar bears in the Chukchi Sea subpopulation.