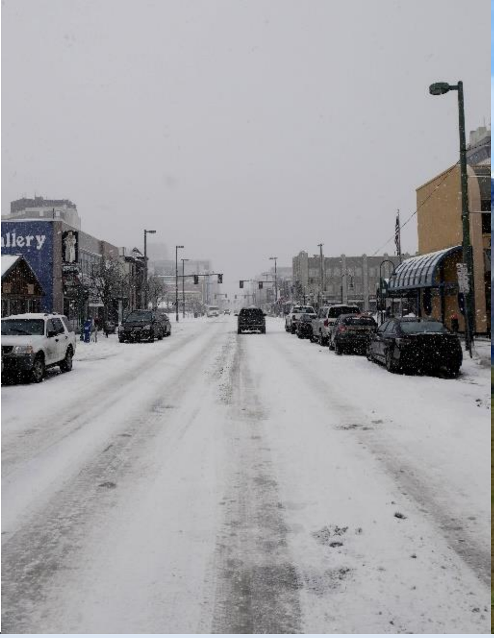
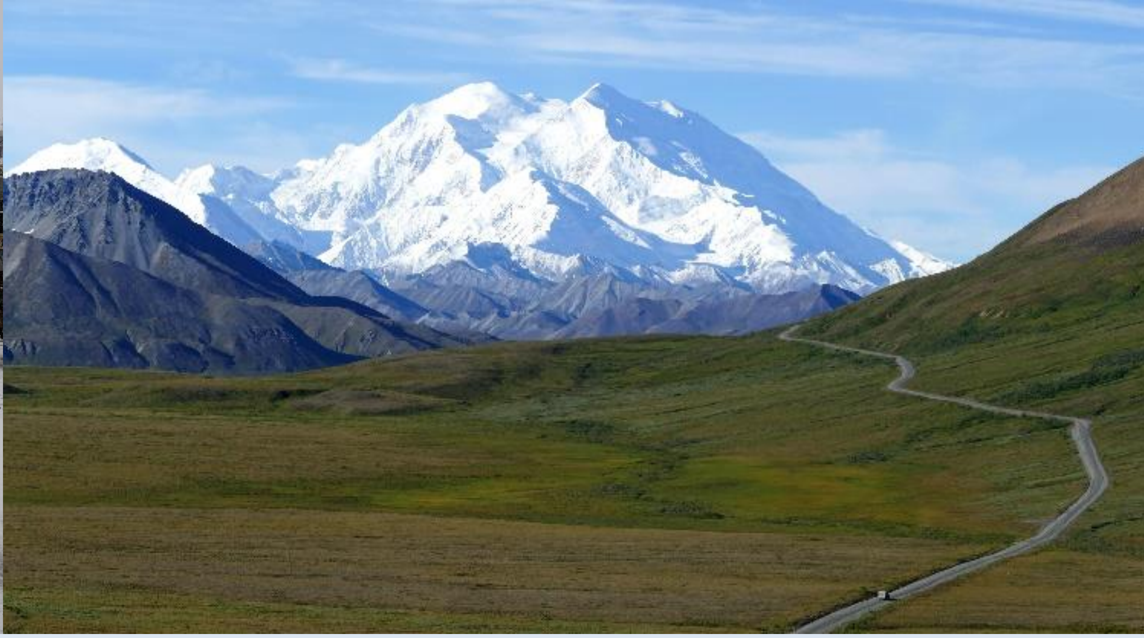
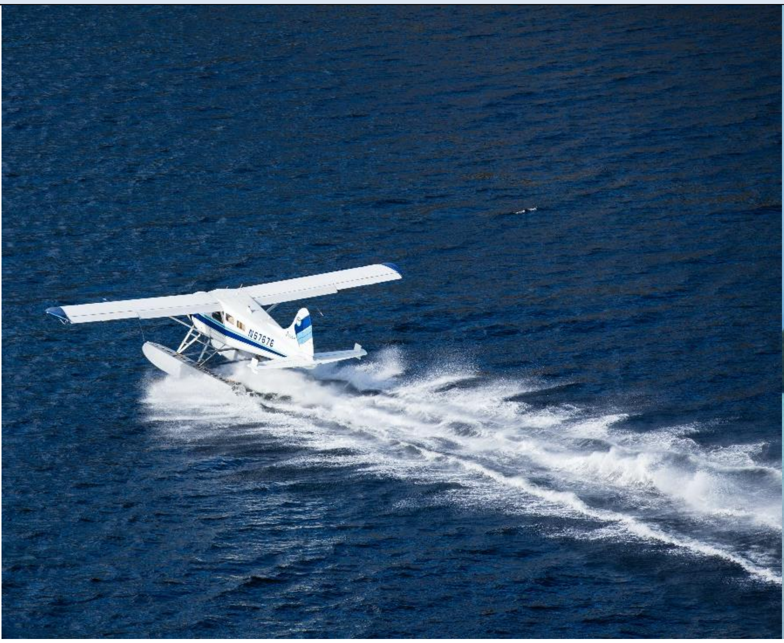




Where Global Warming Meets Local Decision-Making: An Introduction to the Arctic Science Policy Landscape



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Where Global Warming Meets Local Decision Making: An Introduction to the Arctic Science Policy Landscape

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American Meteorological Society

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Executive Summary

The Arctic is one of the fastest warming places on Earth. The consequences of this warming are already felt locally and globally and are expected to intensify over the next few decades. As a result, there is great need for scientists to inform the many policy decisions related to weather, water, and climate (WWC) in the Arctic.

The Arctic has been of enormous interest to scientists and politicians for hundreds or thousands of years because it is home to many Indigenous people, contains unique ecosystems, is rich in natural resources, and is not governed by any one country. Scientifically, the Arctic combines many disciplines of the Earth sciences. Despite the diversity of disciplines, we find a cohesion across international boundaries and fields of expertise that justifies and explains the term “Arctic science”. Politically, the Arctic is characterized by international collaboration and a large proportion of Indigenous people. However, conflicting views on economic development and environmental protection have led to increasing tension among Arctic stakeholders, and have often been at the center of disputes between federal and local policymakers.

This study aims to 1) give an overview of the most prominent organizations involved in Arctic science policy, 2) introduce the most discussed policy issues in the Arctic and how they connect to weather, water, and climate science, and 3) discuss how scientists and policymakers can collaborate with Indigenous peoples to achieve outcomes that better align with interests at all levels of decision making from international to individual communities. This study is based on over 30 virtually conducted interviews with experts and a one-and-a-half-day virtual workshop held on 21–22 July 2021 with about 30 participants and prominent experts, most notably Meredith Rubin (U.S. State Department), David Kennedy (U.S. Arctic Research Commission), and Julie Raymond-Yakoubian (Kawerak).

We find a rich science policy landscape centered on Arctic issues with organizations focused on Arctic science, Arctic policy, and their interactions. At the international level, political issues are most prominently discussed at the Arctic Council meetings. Much of the science coordination occurs within the working groups of the Arctic Council. Only the eight Arctic countries are full members of the Council, leaving Indigenous groups and non-Arctic countries with observing status. Nonetheless, countries tend to engage in more collaboration on Arctic issues compared to many other regions and issues—in particular the United States and Russia. Federally, the number of organizations involved in Arctic science policy reflects the diversity of scientific disciplines and the political issues related to the Arctic. Two organizations stand out in coordinating the U.S. science policy in the Arctic: the U.S. Arctic Research Commission, which reports to the White

House Office of Science and Technology Policy, and the Interagency Arctic Research Policy Committee (IARPC), which coordinates the Arctic science policy activities of 16 agencies and departments. There are even more organizations that work at the state and local level and as non-governmental bodies. Most importantly, Indigenous people in the U.S. Arctic are organized in corporations that are often involved in research, applied science, and science policy. In our research the Ukpeaġvik Iñupiat Corporation and Kawerak were often mentioned as particularly involved in these activities.

The concern that Arctic scientists, regardless of discipline, mentioned most is the lack of observations. The combination of extreme climate conditions with the remote nature of much of the Arctic requires special equipment and makes maintenance difficult. Consequently, in situ observations of the Arctic are sparse and expensive. Satellites are the backbone of much of Arctic research, but they have limits in terms of the type of variables they can observe and depend on ground observations for calibration.

Scientists agree that the most significant progress has been made in the scientific understanding and modelling of sea ice. Improving our understanding of permafrost is identified as the most critical gap in any one discipline. Furthermore, there is significant uncertainty about the effect of Arctic change outside the Arctic, particularly the global ocean circulation and storm patterns in the Northern Hemisphere. Inter- and transdisciplinary work plays a key role to take full advantage of the progress in individual disciplines and to improve our understanding and predictions of the Arctic as a whole. These results will need to be tied together with social sciences and Indigenous knowledge to best inform policy decisions and improve lives in the Arctic and around the world.

The policy issues in the Arctic range from national security and international shipping routes to climate adaptation and natural resources management at the local level. Policy makers need to balance these often-competing interests carefully. As many industries and lifestyles in the Arctic are centered on the use of nature, many political issues can be informed by weather, water, and climate science. For example, all shipping-related issues rely on our understanding of sea ice, sea level, marine weather patterns, tides, and often marine biology. On land, weather, water, and climate science affect transportation, mining, flora, and fauna. Nearly every policy decision in the Arctic is affected by the rapid changes caused by global warming, changes in biodiversity, and land use (often summarized as global change).

Policy decisions also affect what kind of Arctic science is funded, how it is conducted, and who is most likely to benefit from it. This is particularly important in the Arctic where Indigenous groups have historically been underrepresented in the decision-making process. We find a scientific community that is generally aware of this history and willing to improve their processes. However, it is also apparent that few scientists are trained in co-producing knowledge with Indigenous peoples and that many scientific processes are still limiting instead of enabling collaborations between Western scientists and Indigenous knowledge holders. For example, funding requirements can limit the time scientists spend in the field to build the necessary relationships or require university degrees to apply for funding. Furthermore, investments in infrastructure are needed to ensure research is not overwhelming the capacity of smaller communities in the Arctic.

In summary, we find:

- Arctic science is a well-defined term tying together many disciplines through the socio-environmental similarities across the region.
- The greatest potential to advance Arctic science is to enhance Arctic observations, and collaborations across fields and with Indigenous communities.
- The most significant progress has been made in the understanding and modelling of sea ice. The most pressing need is to improve our understanding of permafrost and tying Earth sciences to social sciences.
- Many Arctic policy issues depend on, or could benefit from, Arctic science. In many cases policymakers need to balance priorities ranging from global to local.
- Global warming is affecting almost every decision in one of the fastest warming and changing regions of the world.
- Indigenous people are historically and currently underrepresented in Arctic science and Arctic policy. Relationship building and mutual respect have to be at the center of successful collaborations including co-production of science.
- Traditional funding mechanisms and academic training are often insufficient to enable meaningful collaborations between Western scientists and Indigenous people.

1. Introduction

The Arctic has been of enormous interest to scientists and politicians for hundreds or thousands of years because it is home to many Indigenous people, contains unique ecosystems, is rich in natural resources, and is not governed by any one country. Scientifically, the Arctic combines many disciplines of the Earth sciences: meteorology, climatology, oceanography, hydrology, geology, and glaciology, among others. The description of the Earth system is closely linked to other natural (e.g., biology) and social sciences. Politically, the Arctic is characterized by international collaboration and a large proportion of Indigenous people. However, conflicting views on economic development and environmental protection have led to increasing tension among Arctic countries.

In recent decades, the primary focus of Arctic sciences has been on the fast rate of change of many parts of the Arctic as a result of human-caused climate change. Understanding the Arctic and how it changes has important implications to the local population as well as policy decisions at all levels of government. The focus on the Arctic is reflected in the large number of organizations working in and on the Arctic. In 2020, the scientific efforts in the Arctic culminated in its largest effort yet: the MOSAIC expedition. MOSAIC is an international program evolving around the German research vessel *Polarstern*, which drove into the sea ice and drifted over the course of the year with the ice allowing scientists unprecedented access.

This AMS Program study takes stock of the state of Arctic science, its organizations, and how it is linked to some of the most discussed policy issues in the Arctic. We end with a discussion on how policy decisions affect Arctic science and how scientists can improve their collaborations with people living in the Arctic. This study is based on over 30 virtually conducted interviews with experts and a one-and-a-half-day virtual workshop held on 21–22 July 2021 with about 30 participants and three speakers: Meredith Rubin (U.S. State Department), David Kennedy (U.S. Arctic Research Commission), and Julie Raymond-Yakoubian (Kawerak). The full list of interviewees can be found in the appendix.

2. The Arctic Science Policy Landscape

There is no one generally accepted definition of the Arctic. Scientists and political leaders use different definitions depending on the circumstances. Scientific publications often define the boundaries of the Arctic based on the phenomena they are studying. For example, potential vorticity may be used to define the edge of the polar vortex and the maximum sea ice extent may be a useful measure in glaciology. Politically, the Arctic can be defined using the Arctic Circle (66°33′N), but international bodies have often relied on national and state boundaries. The differences between definitions may seem marginal, but they have the potential to affect scientific findings, include (or exclude) people, and impact other areas of interest such as natural resource deposits. However, the various definitions have no effect on the findings in this study because we focus on the general relationship of Arctic science and policy, which is independent of individual scientific results and exact political boundaries.

The Arctic is characterized by a combination of national land belonging to eight countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States), Indigenous peoples living in the Arctic, and international waters. As a result, there are a large number of institutions and organizations engaged in Arctic policy. While this study focuses on organizations that emphasize Arctic science and policy, relevant decision-making also occurs at all levels of government, the United Nations, and agencies with portfolios that are critical to the Arctic (e.g., the departments of states, energy agencies, etc.). The list of institutions discussed below is necessarily incomplete, focused on science policy from a U.S. perspective on the Arctic, and intended to demonstrate the complex nature of policy-making in the Arctic.

2.1 International Organizations

2.1.1 *Arctic Council*

For decades, countries have generally agreed to a more collaborative approach to Arctic policy compared with other foreign policy issues. In many ways, Arctic policy is similar to the international governance of space, Antarctica, and the open ocean as much of the Arctic Ocean is seen as an area beyond national jurisdiction (ABNJ). The main difference is that individual countries have internationally accepted claims on land in the Arctic and the exact borders of some of the resulting exclusive economic zones (EEZs) are disputed among Arctic countries. The most prominent organization related to international Arctic policy is the Arctic Council. The Arctic Council consists of the eight Arctic countries mentioned above and six Indigenous organizations as permanent participants (the Aleut International Association, Arctic Athabaskan Council, Gwich’in Council International, Inuit Circumpolar Council, Russian Association of Indigenous Peoples of the North, and Saami Council). Only the Russian Association of Indigenous Peoples of the North and the Saami Council have no significant membership in the United States. Additionally, 13 non-Arctic states and a number of intergovernmental, interparliamentary, and non-governmental organizations serve as observers in the Arctic Council. The work of the Arctic Council is split into six working groups with foci ranging from Arctic contamination to sustainable development. The weather, water, and climate community is most closely linked to the work of the Arctic Monitoring and Assessment Program (AMAP), which produces scientific reports on Arctic climate and pollution.

Since 1996, the Arctic Council has produced three binding agreements on maritime search and rescue, marine oil pollution, and scientific cooperation. However, the Council's founding statutes state that it does not have the authority to implement or enforce its guidelines or recommendations. Instead, countries need to sign on to separate treaties to codify any agreement into international law. The activities of the Council are funded by one or more member states. Military security is not part of the work of the Arctic Council.

2.1.2 *Inuit Circumpolar Council (ICC)*

The Inuit Circumpolar Council is one of the primary organizations representing Indigenous people at the international level of the Arctic Council, the United Nations, or similar venues. It represents approximately 180,000 Inuit in the United States, Canada, Greenland, and Russia. The ICC's activities go beyond questions of Arctic science, including climate change, Indigenous knowledge, environmental pollution, sustainability, and biodiversity. The work of the ICC is centered on quadrennial General Assemblies, where most of the programmatic work and elections occur.

2.1.3 *International Arctic Science Committee (IASC)*

Two of the non-governmental observers to the Arctic Council are the International Arctic Science Committee and the International Arctic Social Sciences Association (IASSA). Both organizations promote the exchange of scientific information, international communication, and the assessment of science, and develop guidelines and best practices for scientists working in the Arctic. They are committed to the coequal treatment of Indigenous knowledge and "Western" scientific knowledge. Most Arctic weather, water, and climate scientists are engaged with IASC, while IASSA is focused on social sciences.

2.1.4 *World Meteorological Organization (WMO)*

The WMO has been instrumental in the international coordination of national and regional research related to the Arctic. The Polar and High Mountains group promotes observations, research, and services that lead to improved understanding and predictions of the Arctic. Its signature initiatives are the International Polar Years (most recently in 2007/08), which aim to attract a large number of research projects from across the world to create the most complete picture of the state of the Arctic and typically lead to accelerated advancements in Arctic science.

2.2 National Organizations

2.2.1 *Inter-Agency Coordination*

Many disciplines within the weather, water, and climate science community inform decision-making on a large number of federal policy issues. This is reflected in the number of agencies and departments that operate Arctic programs (e.g., NASA, NOAA, the Department of State, etc.). The coordination of these efforts is divided between the Interagency Arctic Research Policy Committee (IARPC) and the U.S. Arctic Research Commission (USARC). IARPC and USARC were established by the Arctic Research and Policy Act of 1984. IARPC consists of 16 federal agencies, departments, and offices under the leadership of the National Science Foundation and coordinates the federal research efforts in the Arctic to monitor and inform issues at the local, regional, and global level. USARC is part of the executive branch and directly informs the Office of Science and Technology Policy. Every two years, it establishes the administration's policy priorities in the Arctic. Traditionally, these priorities have evolved slowly over time and many USARC commissioners and staffers have served under administrations of both parties. Additionally, USARC provides input into IARPC's 5-year plan, which outlines inter-agency priorities in the Arctic. The experts we interviewed agreed that the collaboration of IARPC and USARC functions well and benefits the legislative and executive branches.

2.2.2 *National Science Foundation*

Concurrent with efforts across agencies, there are many activities related to Arctic science policy within individual agencies and offices. The National Science Foundation has long funded basic geoscience research related to the Arctic through its Polar Program, indicating that NSF views Arctic science as its own discipline instead of a part of the other geosciences. In 2016, NSF announced its 10 Big Ideas project, which included "Navigating the New Arctic". This initiative focuses on convergence research across social, natural, environmental, computing and information sciences, and engineering issues to address the rapid changes currently occurring and predicted for the Arctic.

2.2.3 *National Aeronautics and Space Administration*

NASA supports Arctic research with satellite and airborne missions, and by funding research based on these remote sensing datasets. The two most prominent satellite missions related to Arctic science are GRACE and ICESAT and their respective follow-on missions GRACE-FO and ICESAT 2. The GRACE missions consist of two identical satellites and instruments, which precisely measure the distance between the two satellites (220 ± 50 km). Small changes in the distance can be translated into changes in polar ice sheets and glaciers, the total water stored in soil on land, and other variables. The ICESAT missions primarily measure the exact height of Earth's surface, allowing scientists to study ice sheets and the thickness of sea ice. Additionally, NASA has used airborne field campaigns to collect data with very high spatial resolution or with specialized instruments.

2.2.4 *National Oceanic and Atmospheric Administration*

NOAA performs a number of different activities in the Arctic across its line offices. The National Weather Service is divided into six regions, one of which is focused on Alaska. It provides 24/7 forecasts from three forecast offices. Additionally, the National Ocean Service supports work on navigating the Arctic under changing ice conditions. The NOAA Office of Oceanic and Atmospheric Research (OAR) supports a number of research projects in the Arctic on various time and spatial scales, ranging from observations to theoretical research and model development.

2.2.5 *United States Coast Guard*

The Coast Guard likely represents the largest civil presence in the Arctic among all federal agencies. The Coast Guard requires high-resolution maps and forecasts for its tactical missions, but also supports scientific missions with its planes, ice breakers, and other resources. Reflecting the difficult relationship between Russia and the United States, much of the regular communication between the two countries has been limited to matters of national security, with NASA and the Coast Guard as prominent exceptions. The Coast Guard's connection to Russia, together with its tribal liaison program, has led to the definition of new, more limited shipping routes through the Bering Strait, allowing Indigenous communities to fish and hunt whales safely away from large international ships.

2.3 Indigenous Corporations and Organizations

The relationship between the federal U.S. government and Indigenous peoples in Alaska is fundamentally different from its counterparts in the contiguous United States. Alaska was admitted to the United States as the 49th state in 1959, but the land claims of Indigenous people were not resolved until President Nixon signed the Alaska Native Claims Settlement Act in 1971. As a result of the law 44 million acres (180,000 km^2) and $963 million were transferred to 13 newly formed Native regional corporations and hundreds of local corporations. As a result, there is only one reservation in Alaska, which goes back to 1891. Most Indigenous peoples in Alaska are still shareholders in regional corporations, which engage in different business activities that are often tied to or influenced by weather, water, and climate science (e.g., natural resource extraction). For example, the Ukpeaġvik Iñupiat Corporation has a long-standing relationship with scientists from within and outside of Alaska. Built around a former Navy campus, the organization has a long tradition of working alongside scientists, hosting scientists traveling to the Arctic, and engaging in the scientific decision-making process at federal agencies.

Beside the corporations, Indigenous people have founded a number of organizations that engage with scientists and scientific organizations on many different levels. These local non-government organizations (NGOs) may advocate for the research of specific scientific questions, cooperate with scientists on the co-location of knowledge, develop best practices on how to conduct science in Alaska, connect scientists with local decision makers, and give out their own grants. One of the most prominent examples is Kawerak, a regional non-profit with programs ranging from education to transportation.

2.4 Non-Government Organizations and Academic Institutions

Beyond the organizations described above, there is a rich ecosystem of NGOs, academic institutions, and national laboratories studying the Arctic and engaging in Arctic science policy. Prominent NGOs include the Arctic Research Consortium, the Arctic Institute, and the Polar Program at the Wilson Center, which recently published a report about Arctic Policy[1]. Some of the best-known academic programs on WWC science in the Arctic are located at the University of Alaska Fairbanks, UCAR/NCAR, and the Arctic Program at the Harvard Kennedy School.

In summary, the organizations in the Arctic reflect the sense of unity for the socio-environmental region and the diversity within it. We find many Arctic institutions that emphasize the transnational and interdisciplinary nature of Arctic science. At the same time, the diversity of people, scientific and policy issues, and jurisdictions necessitates a large number of organizations representing different interest groups and specializations.

3. Arctic Science Overview

The term "Arctic science" encompasses many different disciplines and subdisciplines of science. Nonetheless, the experts we interviewed agreed that it is helpful to define Arctic science as a field of study on its own. Arctic science is often characterized by the links between scientific disciplines under the unique circumstances close to the North Pole. The large number of organizations and products focused on Arctic science and science policy is a reflection of this consensus. In this chapter, we will discuss the general difficulties in observing the Arctic as well as where the experts we interviewed see the biggest progress and open questions in Arctic science.

3.1 General Issues in Observing the Arctic

3.1.1 *Sparse observations*

One of the primary concerns of the scientists we talked to is the lack of scientific observations in the Arctic compared with the rest of the world. Many Indigenous tribes have accumulated a wealth of observations of the Arctic over thousands of years. However, these observations typically cannot be easily translated into Western scientific language and numbers.

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[1] https://www.wilsoncenter.org/sites/default/files/media/uploads/documents/Polar_7Csbook.pdf

It is difficult to precisely quantify the density of observations across the globe, but it is evident that the more accessible and more densely populated areas in the midlatitudes and tropics are generally better observed than the Arctic. There are a number of reasons for the lack of observations in the Arctic: 1) the difficulty to access large areas in the Arctic with people and instruments 2) the extreme climatic conditions, and 3) the low population density. All of these factors make observations in the Arctic more expensive and more difficult to install and maintain scientific instruments compared to most locations in the midlatitudes.

The most economical way to observe large areas of the Arctic (and other areas of the world that are difficult to reach) is from space. However, there are limits to the use of satellites to collect data on the Arctic. First, according to EUMETSAT, the use of geostationary satellites is constrained to latitudes below about 60°N. Polar-orbiting satellites can make observations much closer to the pole (although not at the pole) but most locations will be observed only two times per day. Additionally, satellites have limited use to observe the Earth system below the surface. In particular, it is still very difficult to measure properties below the sea surface and below ice reliably from space. As a result, satellites are critical to observe the Arctic, but they need to be complemented with other instruments. Important gaps in time exist in between satellite passes and few satellites can retrieve information very close to the pole, below ice, or in the ocean and Earth's interiors.

3.1.2 *Effect of climate change on observations*

Some of the experts we spoke to expressed concern that climate change will make it even more difficult to observe the Arctic accurately. There are a couple of plausible mechanisms for this theory. First, all satellite measurements depend on algorithms, which translate the electromagnetic signal received in space into physical variables on the ground or in the atmosphere. These algorithms typically depend on assumptions or observations from in situ instruments. As the climate in the Arctic is changing rapidly, we rely on a sparse set of observations to ensure the continued accuracy of the satellite retrievals. The second concern is that climate change will affect sea ice and permafrost in ways that further complicate the logistics of observing the Arctic and therefore lead to even less high-quality information.

3.2 Specific Disciplines

While we encountered many scientists who described their field of expertise as "Arctic science", there are a number of disciplines that inform policy decisions in this region. It is beyond the scope of this report to assess the state of each discipline. Instead, the list below outlines the topics that were mentioned most often by scientists and policy makers and where weather, water, and climate scientists are most likely to contribute significantly.

3.2.1 *Ocean acidification, sea level rise, ocean temperatures*

The basic physics of ocean acidification, sea level rise, and increased ocean temperatures are well understood at the global level. Atmospheric CO_2 emissions lead to larger concentration in ocean water and eventually lower the pH of ocean water. Similarly, a large fraction of the additional warming from anthropogenic greenhouse gas emissions is absorbed by the oceans, whose temperature increases accordingly. Finally, the thermal expansion of ocean water, combined with the increased melt of land ice, leads to rising sea levels. Current research is therefore mostly focused on the local details of ocean acidification, ocean warming, and sea level rise and their effects on the rest of Earth's systems. For example, ocean circulation is already changing in response to climate change. However, there is significant uncertainty about the sensitivity of ocean currents and the global overturning circulation to global warming. Changes in ocean circulation are one example of the effects of global warming on the Arctic and the effects of Arctic changes on the rest of the world. Observed changes have been shown to greatly affect ocean biology. The experts we talked to agreed that linking physical and biological systems in the Arctic at the local level is still a work in progress, but is needed to inform many policy decisions.

3.2.2 *Sea ice interactions and predictions*

Despite its significant decline over the last decades, sea ice is still one of the defining characteristics of the Arctic. Over the last decade, a lot of progress has been made in observing and understanding sea ice dynamics. Additionally, sea ice is now coupled to the rest of the Earth's system in many weather and climate models. While predicting sea ice cover and thickness is still challenging, almost all scientists mentioned this field as the one where scientific progress has been fastest during the last decade.

3.2.3 *Coastal storms and coastal erosion*

One major implication of the decline in sea ice is the potential impact of increases in coastal storms. As the majority of people in the Arctic live on the coasts it is critical to understand and predict the impact of individual coastal storms and the combined effects of all storms over time. In particular, increased coastal erosion has been linked to the combination of coastal storms, decreased sea ice, and thawing permafrost. There is still a lot of uncertainty about the intensity and frequency of future storms in the Arctic.

3.2.4 *Hydrology*

Much of the Arctic contains water in all three physical states throughout most of the year. The landscape is characterized by rivers, lakes, and other bodies of water that are usually much less constrained by human development than in the more densely populated areas. The strong seasonality and large storms lead to complex hydrologic conditions. For example, rain or melting ice and snow upstream can cause flooding, especially if the river is still partly or completely frozen farther downstream. It is therefore critical to understand the dynamics of watersheds, rain rates, and the timing of ice breakups in the Arctic. However, all of these variables are difficult to observe with the relatively sparse instrument coverage in the Arctic. Scientists explained that it can take days until rainfall registers at a stream gauge and often rely on locals to report ice and snow cover.

3.2.5 *Permafrost*

Permafrost describes soils that remain frozen year around, with the exception of a shallow active layer at the top. As melting water cannot easily penetrate the frozen permafrost below, the active layer is often soft and wet. In the Arctic, the depth of the permafrost layer ranges from a few centimeters to several hundred meters (NOAA 2021). However, the state of the permafrost is changing as a result of climate change. As soil temperatures increase, the active layer can become deeper and warmer for longer parts of the year or the permafrost can thaw permanently. There are two important consequences from the increased Arctic soil temperatures. First, changes in the land surface directly affect the living conditions of humans, animals, and plants in the Arctic. For example, thawing soil can cause houses and other infrastructure to sink and become unstable. People and animals often depend on frozen ground to traverse Arctic lands with trucks, cars, skimobiles, or sleds. Flora and fauna of the Arctic are similarly adapted to permafrost conditions. Changes in soil conditions might also further the spread of invasive species that cannot survive extended frost periods. The second consequence of the thawing permafrost is that it might have further impacts on climate change by releasing additional greenhouse gases. There is no doubt that a lot of carbon is bound in Arctic soils, but scientists are still trying to determine how much and how fast this carbon might escape for a given amount of warming. It is clear that answering these questions is critically important to the future of the Arctic and Earth's climate. More recently, scientists have identified additional biogeochemical risks for the Arctic due to the reintegration of materials into the environment as the permafrost degrades (Miner et al. 2021).

3.2.6 *Arctic wildfires*

The risk of wildfires in the western United States is increasingly part of the public discourse. It is less well known that wildfires have also become an issue of concern in the Arctic. The number and size of these events has increased over the past decades. Warming temperatures and increased lightning are among the likely causes for this development. Beyond the direct impact of wildfires on humans, animals, and plants, they also interact in complicated ways with the Earth system. For example, fires can affect water quality, flooding, and landslides. If ash lands on snow or ice surfaces, it can alter the surface albedo dramatically. Weather satellites play an important role in the detection of new fires and in monitoring fires in extremely remote locations. Additionally, detailed weather forecasts are needed to support efforts to contain wildfires and make decisions on possible evacuations. Climate and weather information are also important inputs into the monitoring of plants, soil moisture, and aquifers to identify potential future hotspots and inform decisions on the operation of electricity infrastructure and other risk mitigation strategies.

3.2.7 *Air and water pollution*

The ecosystems of the Arctic are particularly vulnerable to pollution for three distinct reasons. First, long-lasting pollutants tend to accumulate in the Arctic. For example, per- and polyfluoroalkyl substances (PFAS; often referred to as "forever chemicals") have been found in high concentrations in Arctic species. As a result, there is great need for WWC scientists to understand the pathways of pollutants in and out of the Arctic and how they accumulate in various species. Second, the harsh climate of the Arctic leaves little margin for Arctic species to absorb the additional stress from pollution making species. Third, poor infrastructure and difficult weather conditions make cleanup of spills in the Arctic even more difficult and expensive. WWC climate science can inform decisions to minimize the risk of catastrophic pollutants associated with spills and support the cleanup efforts if spills occur. The implications of this work range from international (e.g., fighting oil spills) to the very local (e.g., the health of locally hunted species).

3.2.8 *Global climate change signatures*

The Arctic is warming significantly faster than the rest of the planet. While the Arctic has many unique features, it might still provide a window into the future given the amount of warming the planet will experience due to the greenhouse gas emissions of previous decades. Understanding the details of Arctic amplification and its consequences on the Arctic and beyond is therefore a critical part of climate science. There are many connections between the Arctic climate and the climate in lower latitudes. For example, there is evidence that changes in ocean currents could manifest themselves in a cooling of some parts of the North Atlantic; changes in sea ice are thought to affect the atmospheric circulation in much of the Northern Hemisphere.

3.2.9 *Links to other disciplines and social sciences*

Lastly, weather, water, and climate sciences will be most effective if they are tightly integrated with other disciplines within and outside of science. True Earth system science needs to include biology and geology among other disciplines. However, maximizing the public benefit from weather, water, and climate science requires linkages to many other fields. For example, environmental intelligence has the potential to improve public health and support investments in different areas of the economy ranging from tourism to local infrastructure. Many experts have pointed out the significant opportunities and needs to connect natural Arctic sciences to social sciences and more quantitative approaches to study the Arctic and its inhabitants. These inter- and transdisciplinary approaches almost always require partnerships between academics from different disciplines and often local communities. Few scientists are trained in working with such a broad range of partners—in part because academic institutions rarely incentivize the significant investments of time and resources required for this line of research. Additionally, many common funding mechanisms are not designed to fund interdisciplinary research or the necessary relationship-building process to prepare place-based work with multiple stakeholders. The NSF Navigating the New Arctic program is designed to specifically address these concerns.

3.3 Largest Progress, Biggest Gaps

In summary, the term "Arctic science" describes a broad range of work including, but not limited to, most disciplines within geosciences. The experts we interviewed agree that a lot of progress has been made over the last couple of decades. In particular, our understanding and modeling of sea ice has significantly improved. However, large challenges remain. Our understanding of permafrost and how it may change over time is a key uncertainty. There is also great need to better link the subdisciplinary work of Arctic science—in particular, the connection between the natural and social sciences.

4. Arctic Science Informing Policy

Scientific information is not sufficient for good policymaking because value judgments, political and procedural constraints, and other factors also need to be considered. Nonetheless, there are a number of Arctic policy decisions (ranging from global to local) that can potentially be improved with the best available science. In this section, we demonstrate how the scientific work described above maps onto a variety of policy issues.

4.1 National Security

The importance of the Arctic region for the national security of a number of countries can appear paradoxical or obvious depending on the perspective of the observer. On the one hand, the Arctic countries have declared the Arctic to be a space beyond national interests and collaborate extensively across topics like science and search and rescue efforts. On the other hand, tensions between Arctic countries have been rising, as was demonstrated in the first failure to reach agreement on a final declaration at the Arctic Council ministerial meeting in 2019 because of disagreements over climate change. Russia, Norway, and others have also disagreed over countries' rights to exploit natural resources and shipping routes in the Arctic. Furthermore, in the Arctic Russia and the United States are only separated by a narrow ocean strait, creating enhanced risk for military confrontation. The importance of the Arctic for national security is reflected in the significant military presence in the region. Countries outside of the Arctic have recently also declared their interest in the Arctic, further increasing worries that the Arctic may not be able to serve as an area for international collaboration forever. Most notably, China's self-declaration as a "near Arctic" state was widely seen as intensifying international competition in the Arctic.

Militaries around the world have always sought to use science to their advantage.
The challenging environment in the Arctic makes scientific information about WWC even more critical to the success of military missions. Predictions and observations of the Earth system support activities on land, ice, and in and on water. In the short term, the information may be used to plan missions or better understand and predict the behavior of other countries' troops. On longer time scales, environmental intelligence can ensure the safety of military installation, inform purchasing decisions, and support the overall strategy of the decision makers in the military. The U.S. Department of Defense and its congressional oversight are increasingly aware of the importance of the Arctic to national security and potential vulnerabilities caused by climate change.
It is important to note that, particularly in the United States, the Department of Defense is not just making use of scientific information, but also heavily investing in new research. As a result, scientists may be able to find resources and employment to improve our understanding of the Arctic in the interest of national security and society overall.

4.2 Climate Adaptation

As outlined above, the climate is changing faster in the Arctic than in most other regions of the world. As a result, people and nature have to adapt to changes in their environment faster and more drastically. That's why society might learn about the pros and cons of specific adaptation strategies by looking closely at the Arctic. Scientists caution that the consequences of climate change will vary based on location, ecosystem, culture, lifestyle, and many other factors, but it is still useful to observe how people and nature adapt to the fast-changing climate of the Arctic. Furthermore, new technologies can be developed, tested, and improved under the quickly evolving circumstances. For example, technologies to build on thawing permafrost might become useful in many coastal communities where rising seas affect the stability of foundations.

4.3 Energy and Natural Resources

The economies of many Arctic regions are dominated by the extraction of fossil fuels and other natural resources. The generated jobs and incomes from these activities support many communities in areas with few alternatives. However, extraction of natural resources can cause severe environmental damages to the fragile ecosystems of the Arctic. Jobs in these industries are also among the most dangerous in developed countries. WWC scientists can help regions to minimize the environmental damage caused by natural resource extraction by providing detailed information on topics like watersheds, weather patterns, risk from extreme weather events, animal territories and travel patterns, decay rates of toxins, and many more. This information might also be useful to develop environmental remedy actions, which can be part of the approval process for large industrial developments. Scientists can also play a role in limiting, to the extent possible, the risk associated with some jobs in natural resources extraction. In particular, off-shore extraction companies rely heavily on environmental predictions to decide where to build and how to operate their factories. Ultimately, the decision if, where, and how to extract natural resources in the Arctic will include many inputs that go beyond the WWC sciences. Cultural and historical factors, economic considerations, contractual obligations, and appropriate alternatives are among the many factors that need to be considered. However, accurate and actionable weather, water, and climate information can ground decision-making in the best available information.

4.4 Tourism

The economies of the Arctic are characterized by a relatively small number of industries. Before the COVID-19 pandemic, tourism had developed into a growing part of the economies of many Arctic regions. Tourism promises to bring much needed jobs while avoiding some of the environmental destruction typically associated with the extraction of natural resources. However, tourism, especially in remote areas with extreme climatic conditions, comes with its own challenges. Even small disruptions to the ecosystems of the Arctic can have severe consequences because they tend to be more fragile than the ones in lower latitudes. Cruise ships and whale watching expeditions may affect marine wildlife, pollutants are more likely to accumulate in Arctic species, and hotels, campgrounds, streets, and so on have the potential to negatively impact largely untouched ecosystems. As tourists venture further into the Arctic waters and lands, it will become increasingly difficult to keep them safe. Few cruise ships are built for surprising encounters of sea ice; hikers, hunters, and fishers may not have the necessary skills or equipment to explore the Arctic safely. Geoscientists can play a role in making tourism enjoyable and safe for tourists while also beneficial to local communities, and limiting the environmental impacts to acceptable levels. Forecasting weather, waves, and sea ice conditions can make cruises safer. Careful observations of marine wildlife can support policies that aim to balance the enjoyment of tourists with the interests of the local communities and the protection of the animals. Weather forecasts can help local officials to warn hikers and hunters and, if necessary, support search and rescue missions. Tourism in the Arctic will almost certainly remain centered on outdoor activities and experts expect the number of visitors to continue to increase in volume after the sharp decline due to pandemic restrictions. Weather, water, and climate scientists can inform the decision-making necessary to make tourism a truly positive experience for everyone involved.

4.5 Fishing, Hunting, Conservation, Land Use, and Food Security

As explained above, the Arctic is generally sparsely populated, home to unique ecosystems, and, in the United States, largely owned by federal and state governments as well as tribal corporations. The small fraction of privately owned lands gives policy makers even greater influence on how Arctic lands are used compared to regions in the United States. Balancing the many and sometimes competing interests on land use is a complex task, one that WWC scientists can support with the best available information. For example, Indigenous peoples have hunted and fished in an equilibrium with nature for thousands of years to support their families. The disruption of ecosystems by industry and rapid climate change might require them to adjust their lifestyles to ensure their own survival and that of the animals their cultures rely on. Conservation of Arctic lands is tightly linked to issues of culture, food security, and economic development. WWC scientists can help to identify areas where the ice is thick enough to support hunters, forecast the weather to keep fishers safe, and monitor and predict environmental conditions, which may influence the number and territories of important species.

4.6 International Trade

One of the most publicly discussed topics in Arctic policy is the potential of international shipping routes through the Arctic. As the planet warms and sea ice concentrations and thickness decrease, it will likely become easier, cheaper, and safer for large container ships to connect continents via the Arctic. For example, the route from China to Europe through the Arctic is significantly shorter than the traditional route through the Arabian Sea (Østreng 2010). Given the fact that approximately 80% of international trade is performed by ships, the political uncertainty in some countries along the traditional shipping routes, and the increasingly complicated supply chains (at least before the COVID-19 pandemic), there are great economic incentives to explore commercial shipping routes through the Arctic. WWC science will be at the center of many decisions around these new shipping routes. The environmental impacts of different shipping routes are difficult to calculate. Shorter transit times through the Arctic would result in lower fuel usage and associated greenhouse gas emissions. On the other hand, black carbon emissions close to ice-covered land and oceans can have a warming and pollution effect. Climate scientists can also provide the long-term projections necessary to understand when shipping through the Arctic might become feasible on a large scale. Predictions on shorter seasonal and subseasonal time scales would be required to inform individual shipments and traditional weather forecasts will be critical to the day-to-day operations of any ship in the challenging environment of the Arctic waters. Scientists will need to build on their progress in coupling weather and climate models to sea ice models to produce the high level of accuracy needed to send ships providing goods for some of the largest economies in the world on a regular basis through the Arctic. Additionally, scientists can improve society's understanding of the risks involved in routing a large fraction of global trade through these sparsely populated areas. There is great need to learn more about the potential consequences for Arctic peoples and animals, as well as crews and supporting personnel from accidents, spills, and other complications.

4.7 Infrastructure

Building infrastructure of any kind in the Arctic tends to be significantly more expensive and logistically challenging than in the midlatitudes. Ironically, one reason for the high costs is that a lack of existing transportation infrastructure makes it difficult to deliver material into the region. Other obstacles include a short construction season, harsh weather conditions, and large areas of federally owned and protected land. Under these circumstances it is particularly important to use WWC information to inform decisions on where and how to build infrastructure in the Arctic. Scientists can help choose locations to minimize environmental impact, support the logistics of the construction, and help ensure that structures are likely to last under current and future climate conditions.

5. Policy Decisions Affecting Arctic Science

While there are many Arctic policy issues that can benefit from scientific input, policymakers also have great influence over what kind of science is funded, how science is conducted, who it is performed by, and who benefits from the results. Considering the large number of policy objectives outlined above, policymakers need to balance public investments carefully. It is often difficult to weigh national against local priorities, especially in the sparsely populated Arctic. It is likely that some research can support multiple policy objectives while the direct application of some basic research may not yet be known. It is impossible to make these decisions without acknowledging the impacts of federal policy on the Indigenous population in the Arctic. Indigenous people have lived in the Arctic for thousands of years in unison with nature, and as a result environmental destruction will affect them disproportionately. Thus, it is critical to ensure participation of all stakeholders in the prioritization of research topics. But participation is important beyond the development of the research agenda in the Arctic. Many research programs have strict requirements for advanced university degrees and relationships with universities. Applications can also be bureaucratic and time-consuming. These hurdles were likely developed to ensure funds are spent following best practices and received by extremely qualified individuals. However, many of the most knowledgeable inhabitants of the Arctic have little access to universities and might not have the time or funds to work through multiple layers of bureaucracy. Institutions at all levels should find creative ways to ensure Arctic people can adequately contribute to Arctic research. One step toward equitable access to research is to acknowledge the need for resources to access research grants. A recent example is NSF's decision to fund a Navigating the New Arctic Community Office as part of one of its Great Ideas with the same name.

The Arctic provides a good example of the boundaries of traditional methods to evaluate public policy. One, maybe the most common, way to calculate the validity of government investments is cost-benefit analysis. While there are many variations to determine the precise costs and benefits associated with any given policy, cost-benefit analyses generally find that investing in high-density cities is more cost effective than in rural areas, where a project might only benefit a small number of people. In the Arctic, the high costs of construction and transportation further decrease the results of this kind of analysis. The comparatively low evaluation of Arctic lands manifests itself in the fact that, despite the dramatic environmental destruction and impacts from climate change, NOAA has not detected a single disaster that caused more than 1 billion dollars in damages. It is important to note that cost-benefit analysis always depends on a number of choices, which can affect the result dramatically. For example, experts have long disagreed on how to calculate the value of nature and everything it does for us (often referred to as ecosystem services). Assigning higher values to ecosystem services would likely result in higher cost/benefit ratios in the Arctic.

On the other hand, one might argue that all citizens have a right to the same access to infrastructure, jobs, and many other services independent of the cost of providing such services. By that measure, governments would have to invest almost exclusively in the most rural areas of the country, including the Arctic. However, nobody we talked to suggested applying this method. It is not in anyone's interest to spend enormous resources and disrupt the environment to build six-lane interstate highways to small Arctic towns and villages. The examples above show that great care is needed in evaluating the right level of investment in the Arctic and therefore Arctic science. They also raise the question of fair representation of Indigenous and rural communities in the Arctic in the policy making process. Every democratic society has to balance the right of the majority to rule with the protection of minorities. The latter is particularly important for groups that were never given the opportunity to opt into the system and that have their own culture, language, and traditions. One acknowledgment of these issues is the creation of majority Black congressional districts to ensure Black representation in Congress. However, Alaska elects only one member to the House of Representatives. Federal policy making needs to ensure that Indigenous voices (and those of other minorities) are heard even if their low population limits their direct impact on elections without distorting the interests of the democratic majority too far.

Over the last decade, many scientists, organizations, and other stakeholders have argued that the best form of collaboration between scientists and Indigenous peoples is through co-production of knowledge. This term is based on the assumption that Indigenous knowledge is not just a valuable input to Western science but an equally valid yet separate knowledge base. Progress is then made by effectively combining Western scientific methods with Indigenous knowledge. Almost all experts agreed that it is not necessary or helpful to try to translate Indigenous knowledge into the language of Western science, but that they are two independently valid descriptions of the world.

Recently, the nuances and drawbacks of using co-production of knowledge have become part of the public discourse around Arctic science. The first call for proposals under NSF's Navigating the New Arctic program was interpreted by many as requiring all projects to use co-production of knowledge. The consequences were described in an open letter from four Indigenous organizations—Kawerak, the Aleut Community of St. Paul Island, the Association of Village Council Presidents, and the Bering Sea Elders Group—to the NSF (Bahnke et al. 2021). Indigenous organizations and individuals were approached with a very large number of requests to collaborate just before the deadline to submit proposals. As a result, many felt that these proposals overwhelmed their capacity and did not lead to meaningful collaboration on topics of interest to local communities. Overall, the process revealed some of the necessary conditions for successful co-production of knowledge.

First, while Western scientists and representatives of Indigenous organizations agree that co-production of knowledge is a valuable research method, it does not lend itself to all research questions equally. A genuine interest of all collaborators in the research topic is an important condition for co-production of knowledge. The first call for proposals under the Navigating the New Arctic program led to a number of projects that did not meet the tribes' needs and interests.

Second, co-production of knowledge requires strong relationships between collaborating parties. As Indigenous knowledge is very much tied to the individual Indigenous knowledge holders, building strong working relationships is critical to go beyond the simple exchange of information. Scientists may have to spend significantly more time in the Arctic than is typical for projects that do not aim to co-produce knowledge. Traditional funding mechanisms often provide limited resources to enable the necessary relationship building, extend time in the field, and accept the potentially less certain outcomes of co-production.

Third, formal requirements and a lack of resources can make co-production grants inaccessible to local communities. As mentioned above, traditional knowledge holders are not necessarily trained at Western universities, which means that they often lack the degrees to serve as the primary investigators on grants. Similarly, traditional knowledge holders very often have jobs outside of research, making it more difficult to devote the necessary time and resources to co-production projects. Ideally, it would be at least as likely for local communities to initiate co-production projects as it is for scientists from the outside world. There is hope in the community that the second call for proposals along with the additional resources for the Navigating the New Arctic Community Office are big steps to improve multidisciplinary research in the Arctic. The lessons learned from this program have the potential to inform federal research funding in the Arctic across NSF and in other agencies. Indigenous people have written extensively about Indigenous knowledge and successful collaborations with scientists (Inuit Circumpolar Council 2021, Behe et al. 2020).

Finally, there is widespread acknowledgement that universities rarely prepare early career scientists to work on place-based research and to actively involve the user and stakeholders in their results. There is great potential in collaborations between universities, funding agencies, and stakeholder representatives to train scientists before they start working in the Arctic (and many other communities). This kind of training would not be limited to co-production of knowledge but rather apply to all forms of research. It could help scientists to develop the knowledge, skill, and relationships to conduct their work more responsibly and effectively by knowing how to engage stakeholders, Indigenous communities, and other local authorities. Many agencies already require short courses on the ethics of research. Adding an additional course on the guidelines to collaborate with Indigenous knowledge holders and non-scientists could be a meaningful step forward.

6. Conclusions and Recommendations

The Arctic is diverse with respect to the culture of the people who live there, the natural environment, the economies, and many other aspects. Yet, despite the diversity, there is enough socio-environmental similarity about the most northern parts of the world to make it meaningful to discuss the Arctic as a whole. One representation of this unity is the fact that Arctic science comprises many scientific disciplines that are rarely so tightly integrated in other parts of the world.

There is enormous interest in a number of policy issues in the Arctic. As the result of this interest and the diversity of stakeholders in Arctic policy, many organizations coordinate Arctic science and Arctic policy. One key to understanding the decision-making in the Arctic is the complex interplay of tribal, local, state, federal, and international consequences of policy.

WWC sciences face some unique challenges in the Arctic. The combination of harsh weather conditions, sparse populations, and limited infrastructure make field work more difficult and expensive than in the midlatitudes. As a result, sparse in situ observations are one of the key limiting factors of Arctic science making remote sensing even more important than in the rest of the world. While satellites are also somewhat limited in their ability to observe the Arctic, they make up the majority of WWC observations in this area. Nonetheless, much progress has been made over the past decades. In particular, the understanding of sea ice and our ability to predict it has improved significantly. We emphasize four research areas where continued improvement is needed. 1) The consequences of climate change on Arctic permafrost remain hard to predict and the effect on infrastructure, ecosystems, and future greenhouse gas emissions is potentially large. 2) There is significant uncertainty about the effects of Arctic warming on the global oceans and the frequency and intensity of storms in the midlatitudes. 3) Given the large number of disciplines within Arctic science, there is great potential in further improving interdisciplinary research. Society increasingly demands products and predictions that can only be achieved by successfully linking the progress in individual areas of research. 4) The linkage between the Arctic natural and social sciences is of particular interest to improve the life of the people living in the Arctic.

WWC science has the potential to inform many Arctic policy issues because both traditional Indigenous lifestyles and modern Arctic economies depend more directly on environmental intelligence than many regions in the midlatitudes. For example, shipping and aviation play a much larger role in the Arctic and depend heavily on reliable weather, wave, and sea ice predictions. Additionally, Arctic economies often rely on the preservation and exploitation of natural resources for tourism, hunting, fishing, oil drilling, mining, and others. At the same time, Arctic ecosystems are particularly vulnerable to disruptions, tend to be more affected by pollution in and outside the Arctic, and are exposed to some of the fastest climatic changes on the planet. Fortunately, many Arctic research activities can inform more than one policy issue. Sea ice predictions may be applicable to military vessels, cruise ships, oil tankers, fishing boats and wildlife. Identifying the research with the broadest possible applications can be one way to maximize the use of research investments but requires great coordination of funding agencies and organizations.

However, most investments won't benefit everyone equally, which raises three important questions. 1) Who sets the research agenda? There is great value in participatory practices that reach as many stakeholders as possible to accurately determine the greatest needs—especially of minorities and local populations, who may have limited power at higher levels of government. 2) What is the best process to prioritize between different policy issues, levels of government, and regions? The Arctic is a great example for the limits of economic analysis to justify funding decisions. Common cost-benefit calculations often characterize investments in the Arctic as an inefficient use of funds due to the expensive infrastructure and sparse populations. On the other hand, demanding the same access to infrastructure would lead to absurd levels of spending. Economic analysis can still be valuable in comparing different investments in the Arctic, but careful consideration is required to balance different regions. 3) How can Western scientists and Indigenous knowledge holders collaborate to benefit both groups and society overall? There is broad consensus that both Western science and Indigenous knowledge can meaningfully contribute to Arctic science. However, not every issue benefits equally from the deep collaboration referred to as co-production of knowledge. In cases where co-production is called for, scientists need better training to work successfully alongside Indigenous people, and grants to support the necessary relationship building. Additionally, Indigenous knowledge holders often lack the resources or formal degrees to access research funding, leaving them to respond to the request of scientists instead of initiating the critically important work to support their communities.

The Arctic is of great importance to the AMS community because there are few places where WWC sciences can inform such a large number of policy issues ranging from national security to the local adaptation to fast climate change. Consequently, there is great interest and the need to advance Arctic science. Scientists are increasingly tasked to connect their expertise with other natural and social sciences as well as Indigenous knowledge to produce the most applicable results possible. Policy makers and funding agencies balance the need to support many disciplines and to inform many policy decisions against the backdrop of high costs of Arctic research.

References

Bahnke, M., V. Korthuis, A. Philemonoff, and M. Johnson, 2021: Letter to the Navigating the New Arctic Program. Arctic Today, accessed 25 October 2021, https://www.arctictoday.com/wp-content/uploads/2021/02/2020-03-19-NNA-Letter-Final-1.pdf.

Behe, C., R. Daniel, and J. Raymond-Yakoubian, 2020: Understanding the Arctic through a co-production of knowledge. Kawerak, Inc., accessed 25 October 2021, https://kawerak.org/co-production-of-knowledge-in-research-valuing-traditional-knowledge/.

Inuit Circumpolar Council, 2021: Application of Indigenous Knowledge in the Arctic Council. Inuit Circumpolar Council–Alaska, accessed 25 October 2021, https://iccalaska.org/wp-icc/wp-content/uploads/2016/03/Application-of-IK-in-the-Arctic-Council.pdf.

Miner, K. R., J. D'Andrilli, R. Mackelprang, A. Edwards, M. J. Malaska, M. P. Waldrop, and C. E. Miller, 2021: Emergent biogeochemical risks from Arctic permafrost degradation. *Nat. Climate Change*, **11**, 809–819, https://doi.org/10.1038/s41558-021-01162-y.

NOAA, 2021: Land—Permafrost. Arctic Change, accessed 21 October 2021, https://www.pmel.noaa.gov/arctic-zone/detect/land-permafrost.shtml.

Østreng, W., 2010: The Northeast Passage and northern sea route. Arctis Knowlege Hub, accessed 25 October 2021, http://www.arctis-search.com/The+Northeast+Passage+and+Northern+Sea+Route+2.

Appendix

List of experts who contributed to this study, in alphabetical order. The organizations represent the primary employers at the time of the interview/presentation.

1. Emma Arsenault, Polar Knowledge Canada
2. Carolina Behe, Inuit Circumpolar Council
3. Mia Bennett, University of Hong Kong
4. Michael Brady, National Geospatial-Intelligence Agency
5. Lawson Brigham, Wilson Center
6. Ben DeAngelo, National Oceanic and Atmospheric Administration
7. Sarah Dewey, Harvard Belfer Center
8. Hajo Eicken, University of Alaska Fairbanks
9. Kaare Erickson, Ukpeaġvik Iñupiat Corporation
10. John Farell, US Arctic Research Commission
11. David Grimes, Grimes Consulting Group
12. Colene Haffke, National Aeronautics and Space Administration
13. Victoria Herrmann, The Arctic Institute
14. Larry Hinzman, University of Alaska Fairbanks
15. Marika Holland, University Corporation for Atmospheric Research
16. Halla Hrund, Harvard Belfer Center
17. Thomas Jung, Alfred Wegener Institute
18. Brendan Kelly, Study of Environmental Arctic Change
19. David Kennedy, US Arctic Research Commission
20. Anna Kerttula de Echave, National Science Foundation, retired
21. Eva Kruemmel, ScienTissiME
22. Amanda Lynch, Brown University
23. Zen Mariani, Environment and Climate Change Canada
24. Hal Maring, National Aeronautics and Space Administration
25. Andrey Petrov, University of Northern Iowa
26. Allen Pope, International Arctic Science Committee
27. Julie Raymond-Yakoubian, Kawerak
28. Ann Robertson, Office of Senator Murkowski
29. Meredith Rubin, US Department of State
30. Krysti Schallenberger, Alaska’s Energy Desk, KYUK
31. Zachary Schulman, US Coast Guard
32. Abby Smith, University of Colorado
33. Sandy Starkweather, NOAA ESRL
34. Kristin Timm, University of Alaska Fairbanks
35. Celine van Breukelen, National Weather Service
36. John Walsh, University of Alaska Fairbanks
37. Gifford Wong, Science and Technology Policy Institute


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