An Overview of Advisory Studies for the Office of Polar Programs

ADVISORY COMMITTEE TO THE OFFICE OF POLAR PROGRAMS

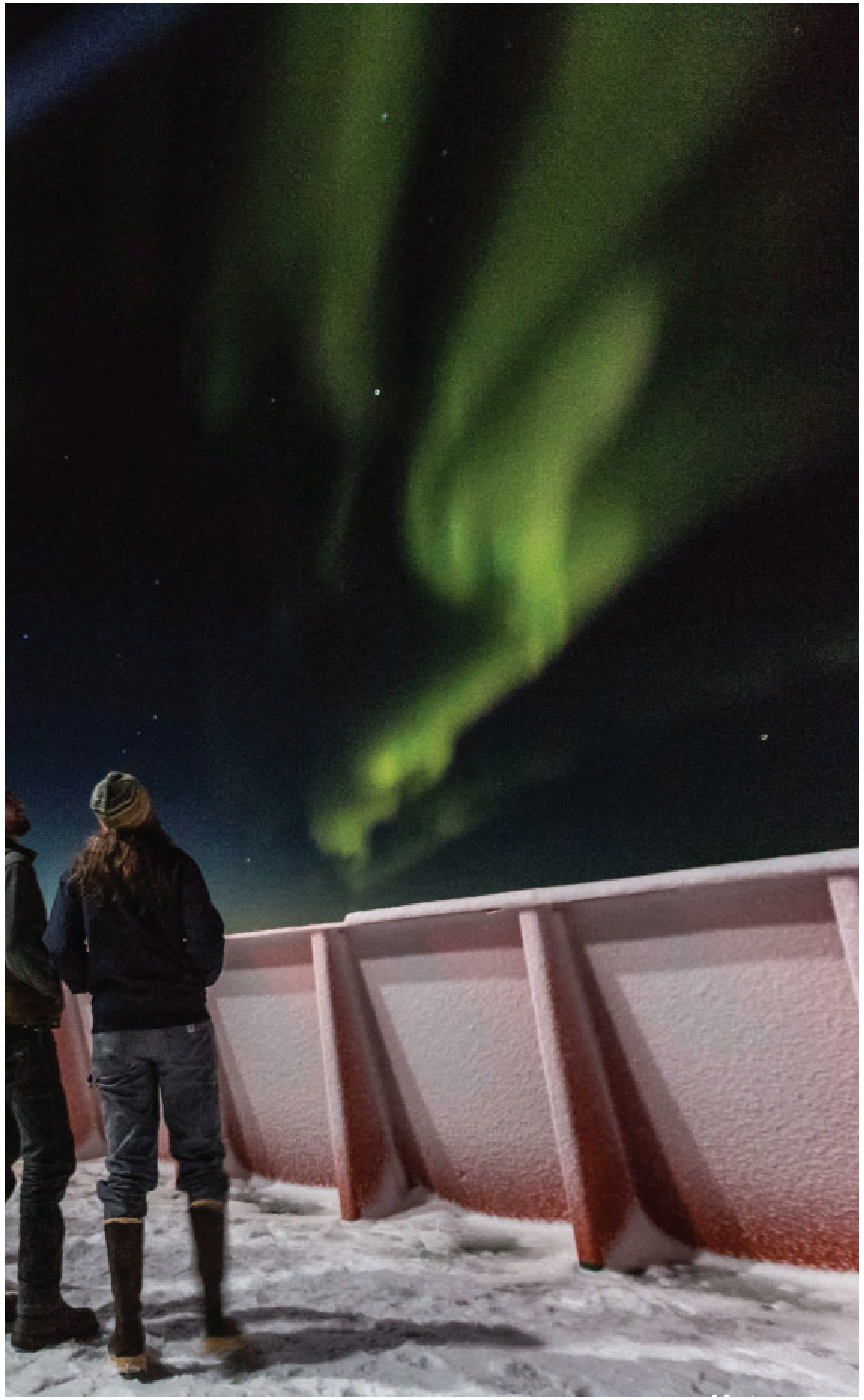
Covering 2012 - 2019

An Overview of Advisory Studies for the Office of Polar Programs

OVERVIEW

Purpose

The Office of Polar Programs (OPP) judiciously allocates resources to a number of competing demands among a wide range of merit-worthy research topics and research support and facilities in the polar regions. The Advisory Committee for the Office of Polar Programs (AC OPP)[1] developed this high-level synthesis of contemporary polar advisory studies, to help inform science funding leadership, the Advisory Committee for Geosciences and other NSF Advisory Committees, and additional stakeholders regarding community-developed recommendations for OPP. By collating into a single document currently recommended priorities, along with the study references, we hope to facilitate understanding of OPP's broad purview and investment drivers. This overview is not meant to supplant the comprehensive advisory documents synthesized here and the reader is referred to the complete reports for fuller detail supporting the summary that follows.



Cover image: The Gerlache Strait between Anvers Island and the Antarctic Peninsula. Photo by Zee Evans.

Left: Passengers on board the National Science Foundation research vessel *Nathaniel B. Palmer* observe auroras in the winter sky. Photo by Ben Adkinson.

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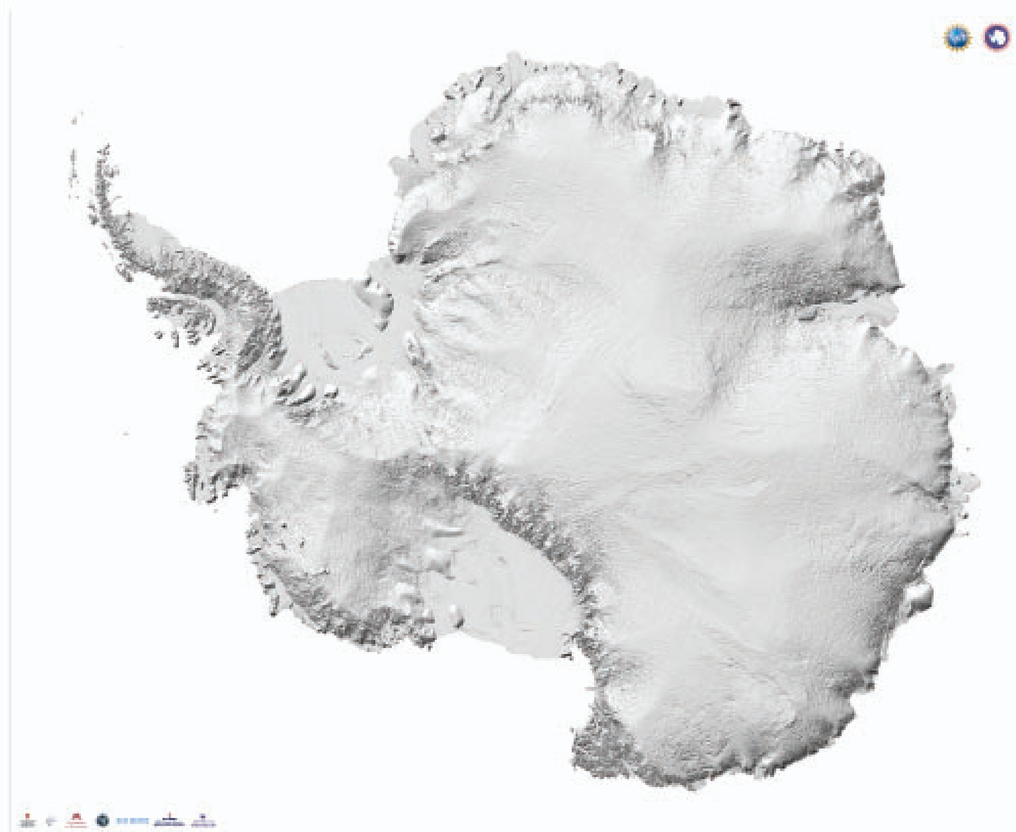
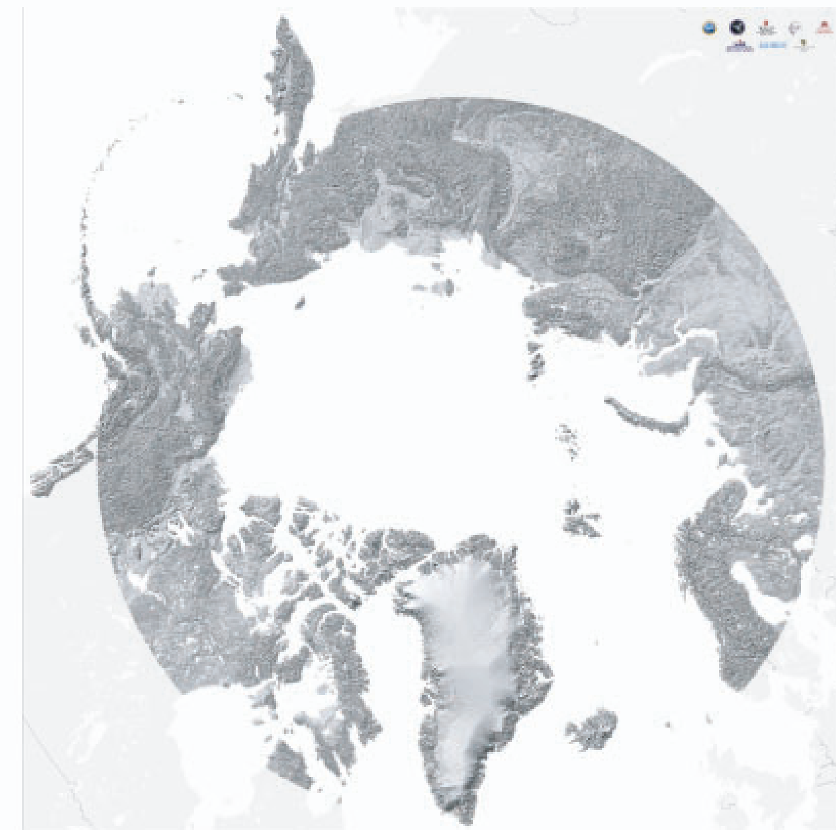




The Reference Elevation Model of Antarctica (REMA) (https://www.pgc.umn.edu/data/rema/) (left), and the ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/) or digital elevation model (DEM) (right). Both illustrate the unique landscape in which polar scientists work. Figures by Polar Geospatial Center using data from the NSF-National Geospatial-Intelligence Agency supported ArcticDEM and REMA projects.

Introduction

The National Science Foundation (NSF) OPP provides a critical nexus for the support of our Nation's world-leading polar research, i.e., research in and about polar regions. Although geographically defined, OPP's purview encompasses nearly all of the disciplines supported by NSF. Furthermore, OPP has nationally significant operational and geopolitical responsibilities. Thus, it is incumbent on OPP to seek advice broadly to ensure that it supports the highest quality and most important science that can only be conducted in or about polar regions.

Building on a hard-won and productive knowledge base, scientists foresee the exciting potential for future fundamental explorations and discovery in and about polar regions that are particularly relevant to decision-makers. Although remote, polar regions exert important global influences that affect weather and climate, natural resource accessibility, and socio-economic systems. These regions are connected through ocean circulation, spatial and temporal disposition of sea ice, and glacial ice and permafrost, a myriad of biogeochemical processes operating in the marine and terrestrial ecosystems, space, and atmospheric weather systems, and regional and global economics and geopolitics. The unique polar environments also enable discoveries in the fundamental sciences.

To craft this advisory overview, the AC OPP drew from the most current reports published by the National Research Council (NRC) of the National Academies of Science, Engineering, and Medicine reports and interagency and international science planning documents noted in Appendix 1. The AC OPP also reviewed the 2014 planning effort prepared by the Geosciences Advisory Committee, Dynamic Earth: GEO Imperatives and Frontiers 2015–2020.[2] Our review examined documents developed by various research communities within the past five years and the 2012 Blue Ribbon Panel Report[3] regarding Antarctic infrastructure and logistics, which remains relevant to long-term facilities investments and subsequent advisory reports. The AC OPP also considered how this current community-based advice aligns with NSF's 10 Big Ideas,[4] which are currently guiding NSF strategic investments.

This document summarizes current pressing research drivers in the form of ten crucial and broadly-encompassing questions. Underlying each question are numerous topics that can drive science proposal submissions, which will be assessed through NSF's "Gold Standard" Merit Review system. We also discuss a number of common major research support requirements that emerged from these science drivers, including infrastructure and logistics, data and cyberinfrastructure, education, diversity and inclusion, as well as collaborations and partnerships.

The Advisory Committee recommends that OPP staff continue to build on and strengthen efforts to make these science and logistical support objectives broadly

The Office of Polar Programs (OPP) is part of the Geosciences Directorate along with the Division of Atmospheric and Geospace Sciences (AGS), the Division of Earth Sciences (EAR), and the Division of Ocean Sciences (OCE). As of the production of this document, OPP is structured as follows:

Front Office: Comprises leadership, administrative, budget and IT systems support, education liaison, and outreach and communications staff

Arctic Sciences (ARC): Comprises Arctic Social Sciences, Arctic Observing Networks, Arctic Natural Sciences and Arctic System Science programs as well as the Arctic Research and Logistics Support programs. Responsible for the year-round Summit Station in Greenland, assisting in support of facilities in Alaska, as well as arranging for research access and support elsewhere in the Arctic. Contributes a coordinating role for research support on U.S. and other vessels operating in Arctic waters.

Antarctic Sciences (ANT): Comprises Astrophysics and Geospace Sciences, Ocean and Atmospheric Sciences, Earth Sciences, Glaciology, Organisms and Ecosystems, Integrated System Science, and Instrumentation and Research Facilities programs.

Antarctic Infrastructure and Logistics (AIL): Responsible for coordination and oversight of Antarctic infrastructure and logistics on behalf of the Nation including operations of three year-round stations, research access and support throughout the Antarctic, light ice-breaking research vessel (R/V) Nathaniel B. Palmer and ice-strengthened Antarctic research and supply vessel (ARSV) Laurence M. Gould, and enlisting federal and private support services for the USAP.

Polar Environmental, Safety, and Health (PESH): Develops policy for and oversees environmental stewardship, safety, and occupational health for both polar regions.

known to the research community, as well as develop new and diverse expertise for achieving polar research priorities. As a formal advisory body,[1] the AC OPP welcomes community feedback as we endeavor to help OPP and NSF identify areas worthy of future advisory focus.[5]

Background

> ***NSF's Mission***
> *"To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense; and for other purposes."*[6]
>
> ***NSF's Vision***
> *"A Nation that is the global leader in research and innovation."*[6]

The Office of Polar Programs (OPP) promotes the National Science Foundation (NSF) mission and vision by supporting "creative and innovative scientific research, engineering, and education in and about the polar regions, catalyzing fundamental discovery and understanding of polar systems and their global interactions to inform the nation and advance the welfare of all people."[7] The OPP research portfolio encompasses fundamental and system level studies across nearly all areas of research supported by NSF that are best done or can only be done in and about the polar regions.

To facilitate polar research on behalf of NSF and other communities, OPP exercises operational responsibilities over infrastructure, logistics, health, safety, environmental stewardship, and international collaboration. In the Antarctic, OPP executes the presidential memorandum[8] that charges NSF with managing the U.S. Antarctic Program (USAP) on behalf of the nation. In the case of the Arctic, the Arctic Research Policy Act[9] names the NSF Director as the chair of the Interagency Arctic Research Policy Committee (IARPC); OPP supports the IARPC chair role and promotes active interagency engagement toward a well-coordinated national Arctic research agenda.

Through participation in U.S. delegations to the Antarctic Treaty System[10] and in activities related to the Arctic Council,[11] OPP supports the Nation's geopolitical interests. OPP additionally leverages its investments through collaborative partnerships with educational and research institutions and various local, state, federal and international entities.

Science has long been a fundamental component of international cooperation in the polar regions. The International Geophysical Year in 1957-58 led directly to the formation of the Antarctic Treaty in 1959.[10] In subsequent years, science supported within the Antarctic Treaty System[10] lead to the negotiation of the Convention for the Conservation of Antarctic Marine Living Resources and the creation of the Scientific Committee on Antarctic Research. Similarly, the Arctic Council grew directly out of the cooperation fostered by the International Arctic Science Committee, which was guided by NSF leadership.

RESEARCH DRIVERS

The AC OPP synthesized research themes, from currently relevant advisory reports (as cited), in the form of ten overarching research questions below. These collectively capture the priority research areas intended to guide OPP investments and are not listed in any particular order.

How have polar biota evolved in extreme environments, and how will they adapt to a changing climate?[4,6,12,13,14] Organisms evolve in response to their environment and to biological interactions. The extreme environmental settings of the polar regions provide unique selection pressures for studying phenotypic evolution and its genomic and transcriptomic underpinnings. In addition, these environments provide natural laboratories for investigating organismal and ecosystem responses to abruptly changing climate conditions and for paleo-reconstructions of these responses. Understanding the adjustments of organisms and ecosystems to past and current environmental changes will lead to a broader understanding of the evolution, the limits, and the distribution of life, and thus provide fundamental insights on the rules of life operating in both polar and non-polar regions.

How will Arctic environmental change, such as decreasing sea ice and permafrost, affect regional and global socio-economic systems? [2,4,13,15,16] Decreasing sea-ice is increasing accessibility to marine transportation corridors, fishing areas, and mineral resources, while inciting changes in fisheries, tourism, and potentially increasing contaminant concentrations. Thawing permafrost will entail new engineering challenges associated with destabilized coastlines and terrestrial landforms. These changes will likely impact the cultures, governance structures, and interactions of Indigenous communities with other Arctic and non-Arctic communities. The potential for resource and infrastructure development, alternative shipping routes, exclusive economic zone claims and security concerns will affect the geopolitical interests of both Arctic and non-Arctic nations in ways yet to be determined.

How are Arctic societies responding to globalization?[4,13,17] Arctic Indigenous people and other Arctic residents experiencing simultaneously evolving economic, political, technological, energy, information, and environmental systems. These globalizing forces interact with enduring local foundations of kinship, cultural/linguistic identity, ties to the land, and other endowments of Indigenous knowledge. Social and natural sciences must be applied to understand such interactions to inform societal trajectories and future choices. Such work can entail collaborative research and knowledge co-production with Arctic residents; convergent research on socio-ecological systems involving Indigenous knowledge; community health; food and energy

Right: A young girl in a Dukha reindeer herd camp in Khovsgol Aimag, Mongolia. Photo by Todd Surovell.

security; interdisciplinary archaeological research that yields data on past climate, ecosystem states, and human responses to change; collaborative heritage and linguistic preservation; and ethical research and data management.

What is the connection between the poles and global atmospheric weather and climate patterns?[4,13,14,16,18] The polar regions affect atmospheric circulation and the planet's energy budget. Arctic amplification, the disproportionately large warming in the Arctic relative to mid-latitudes, will strengthen as greenhouse gas concentrations increase. Currently it is uncertain how this warming, which changes planetary scale temperature gradients, affects weather patterns over the Northern Hemisphere, including the United States. Tropical oceans and monsoonal circulations appear sensitive to processes occurring over Antarctica and the Southern Ocean. Research is needed to examine these potential linkages, the magnitude of their influences on weather elsewhere relative to non-polar factors, the spatial and temporal dimensions of the influence, and the type of weather events most susceptible to polar influence.

What are the rates and magnitudes of sea level rise associated with the loss of polar land ice?[2,4,6,12,14,16] Knowledge about how ice sheets have changed in the past in response to natural forcing, and how they are changing now and in the future in response to anthropogenic forcing, are critical for understanding and projecting potential sea level rise and its impact on coastal regions globally. Of particular concern are potential large sea-level-rise contributions of the West Antarctic and Greenland ice sheets. Understanding the connections between ice sheet and ocean processes requires accounting for the complex coupling among the atmosphere, ocean, sea ice, ice sheet, and solid Earth, all of which control important aspects of ice-sheet behavior. Observations on the longest timescales are available only through paleoclimate archives such as paleo-shorelines, exposure dating, ice cores, and sediment cores. Both paleo- and modern observations guide modelers using state-of-the-art Earth system models. For some problems, such models must be run at very high spatial and temporal resolutions, which depend on significant computing and data infrastructure, to resolve critical, physical processes. Computationally and conceptually, these problems represent grand multi-scale, multi-variable challenges.

How will reductions in sea ice, glaciers, and ice sheets, affect the global ocean circulation, climate, and global carbon and biogeochemical cycles? [2,4,12,13,14,15] Melting of Arctic sea ice and polar ice sheets (Greenland and Antarctica) as well as glaciers and ice caps, cause surface freshening of high latitude oceans. Changes in temperatures and salinity alter the vertical stratification of the ocean, affecting carbon and other biogeochemical cycles and climate through changes in marine productivity, ecosystem structure, deep-water formation rates, and adjustments in the global overturning ocean circulation. However, the magnitude and rates at which melting and freshening occur, and the subsequent oceanographic changes, remain uncertain. The research community needs to better understand deep-ocean ventilation processes, the present-day composition of high-latitude marine communities, and patterns and rates of marine production and biogeochemical cycles. Marine community structure and production rates are also affected by ocean acidification, which is exacerbated by ice melt and increased concentrations of atmospheric carbon dioxide.

How do changes in permafrost affect the hydrologic cycle in the Arctic, the carbon cycle, and global climate? [2,4,13] Permafrost underlies ~20% of the global land surface but contains as much organic carbon as found in the rest of the world's soils. Thawing permafrost promotes carbon loss from this massive reservoir, with

Left: Scientist Vasilii Petrenko loads an ice melter at Taylor Glacier, Antarctica. Photo by Vasilii Petrenko.

Right: A small boat navigates shallow water below ice wedges and baydzerakhs (mounds of thawing Pleistocene permafrost soils) at the riverbank exposure of Duvannyi Yar on the Kolyma River in the Siberian Arctic. Photo by Chris Linder.

large, but uncertain, feedbacks on climate and the global carbon cycle. A reduction in permafrost will also alter hydrologic and biogeochemical cycles and lead to changes in the productivity and species compositions of Arctic terrestrial and marine ecosystems in unknown ways. How permafrost influences these processes, the rates at which it is thawing, and how these rates vary spatially are not yet fully understood. Moreover, how carbon loss from permafrost will be modified by changes in terrestrial vegetation and marine ecosystems is unresolved. Research is needed to better incorporate permafrost-related processes into ecosystem, climate, and earth system models to improve the predictive capability of these models.

How does society more efficiently observe and measure the polar regions?[2,4,16] In spite of the array of field stations and logistical support, *in-situ* measurements in the polar regions are limited and seasonally biased because observations are often obtained during periods when polar access is convenient and affordable. Many of the research drivers outlined here require understanding the broader spatial-temporal variability of the rates and processes governing transfers of energy and matter. To study a wider geographic and temporal range, will require spatially-distributed and long-term measurement networks generating year-round data. Monitoring allows quantifying the natural variability of systems so that change can be reliably detected. Moreover, prompt data delivery provides an "early warning system" of abrupt or hazardous changes, which

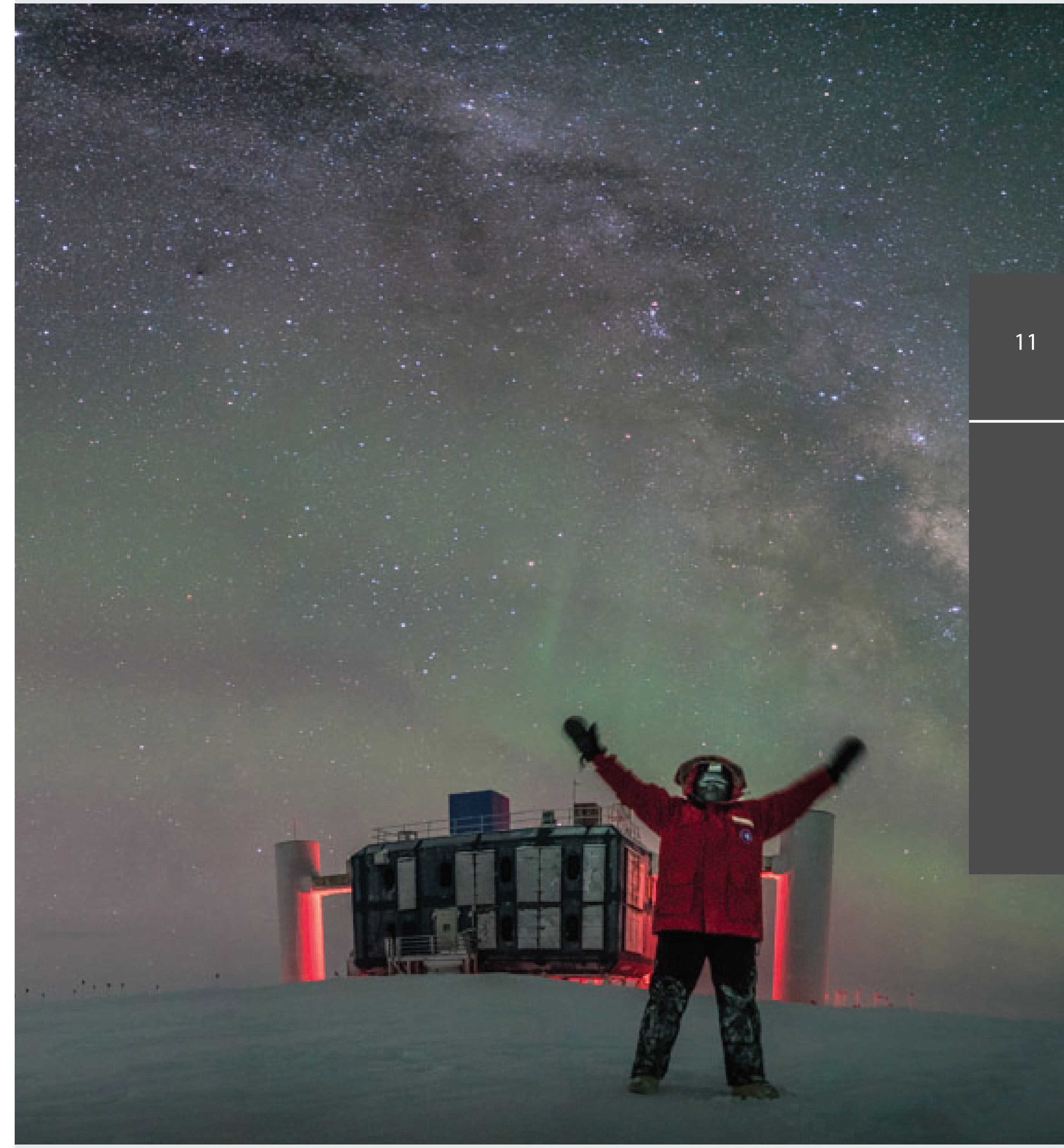
Left: Loreena Edenfield and Alice Orlich measure sea ice thickness during the R/V *Sikuliaq's* 2015 Ice Trials in the Bering Sea. Photo by Roger Topp.

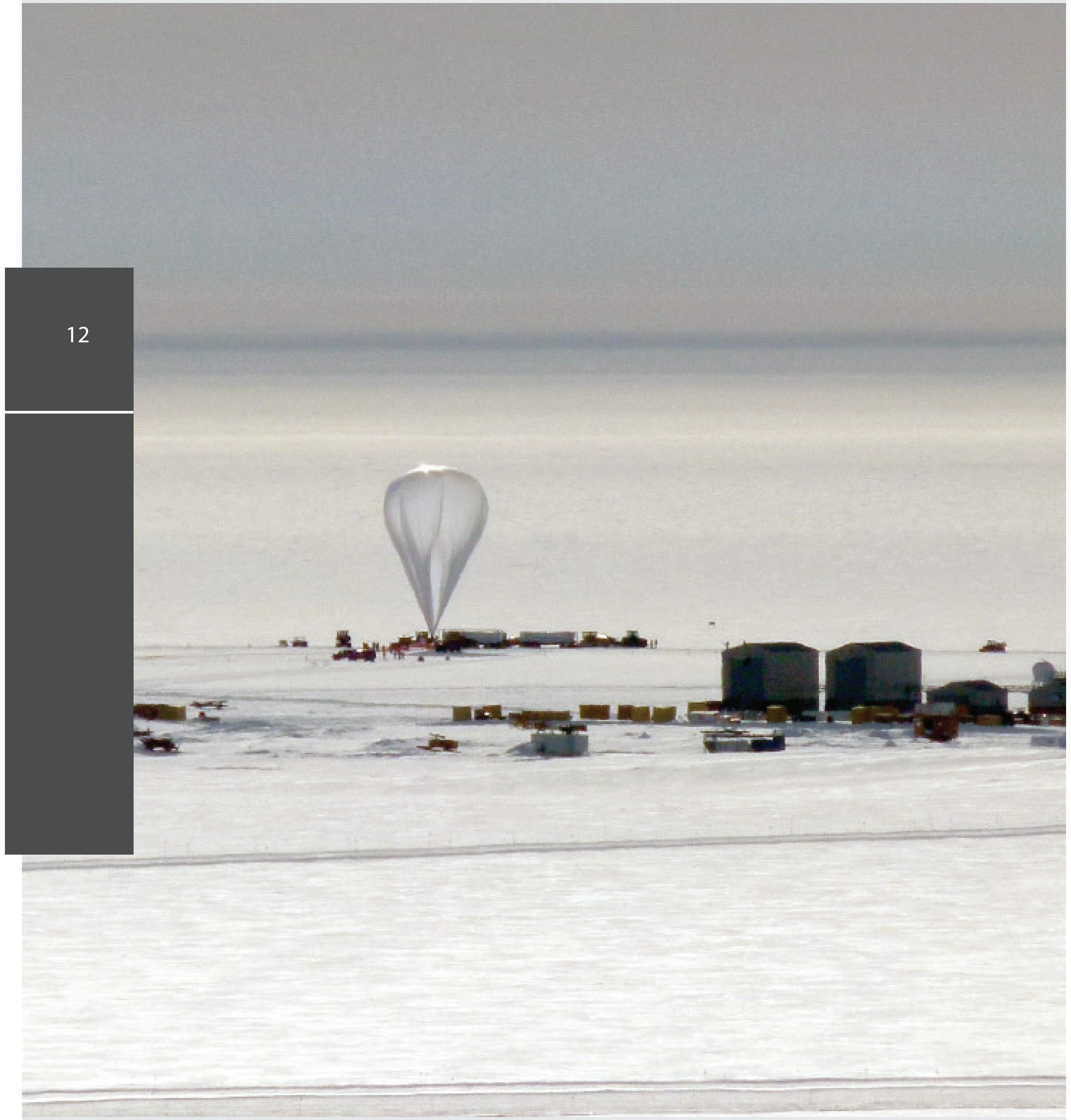
Right: Martin Wolf, a member of the IceCube science team, greets the world with a dramatic backdrop of the aurora australis and Milky Way over the South Pole. Photo by Martin Wolf.

enable informed and timely societal responses. Establishing early warning monitoring networks entails developing new instruments and autonomous sensors for fixed and/or mobile platforms, innovative data retrieval techniques, robust cyberinfrastructure, and paleoclimatic investigations that provide a historical perspective on adjustments to past climate changes. Computational methods of observing system simulation and optimal network design are powerful tools to guide network implementation. In collaboration with NSF's Office of Advanced Cyberinfrastructure (Computer & Information Science & Engineering Directorate) and Industrial Innovation and Partnerships (Engineering Directorate), OPP needs to leverage the diverse talents of the research and engineering communities to develop and implement cutting-edge (and potentially high economic payoff) technologies. In addition, a unique challenge to OPP will be to foster the capacity to co-produce and incorporate Indigenous and local knowledge and observations into this research infrastructure.

What processes govern the evolution, the structure, and the fate of the universe (astrophysics and cosmology)?[2,3,4,12,14,19] Understanding the evolution, the structure, and the fate of the universe has perpetually interested humankind. This knowledge is of vital importance in understanding our solar system and planet, and the fundamental physical principles upon which life depends and has evolved. The astrophysical and cosmological data necessary to foster this knowledge are collected from a variety of space- and terrestrial-based sensor systems that measure across broad spectra of subatomic particles and radiation emanating from deep space. Antarctica is the world-leading site for measurements of the Cosmic Microwave Background, the oldest light in the universe, and for measurements of the highest energy neutrinos in the universe. OPP's support of these measurements is and will continue to be vital in delivering new advances in the era of multi-messenger astrophysics.

How does space weather affect human life and the technological systems upon which society depends?[2,3,4,14,20] Earth's space environment responds to solar variations, which have the potential to disrupt power grids and communication systems. Quantifying the effect of these interactions on human activities and developing





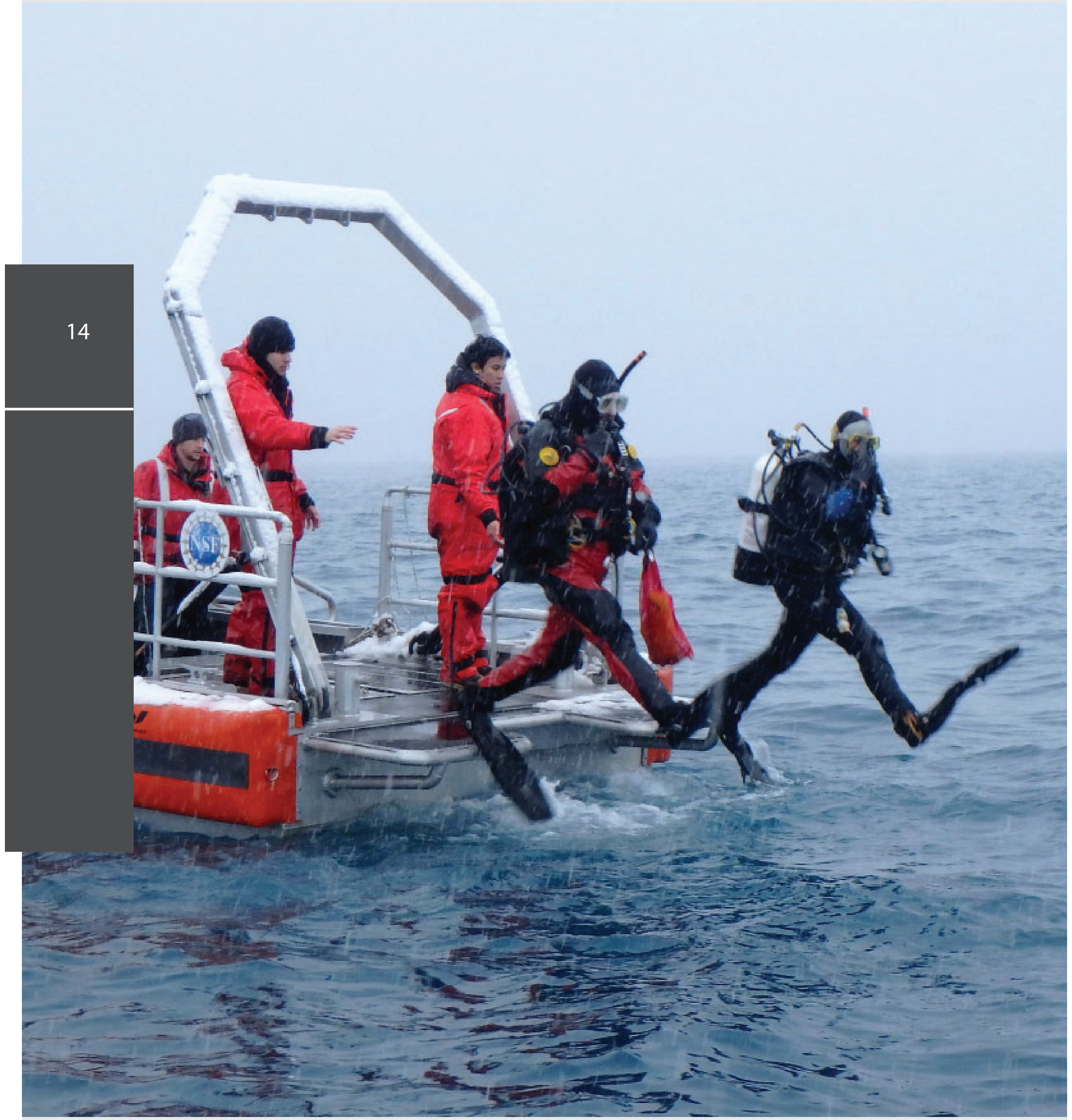
predictive capability of their onset and impacts are critical. The Arctic and Antarctic provide critical vantage points for the study of the interplay of the Sun's dynamical processes, the solar wind, and the Earth's ionosphere and magnetosphere. OPP can stimulate this research through continued collaboration with NSF's Atmospheric & Geospace Sciences Division's *Solar, Heliospheric, and Interplanetary Environment (SHINE)* program and interagency collaborations with DOD, NASA, NOAA, and private industry.

These research priorities were synthesized from current reports developed by the science community and other experts. Several of these research priorities are well-aligned with many of NSF's 10 Big Ideas; a set of 6 research ideas and 4 process ideas that are strategically driving new investments.[4] Table 1 demonstrates the extensive overlap of OPP priority research drivers with the NSF 10 Big Ideas. Table 1 also includes the research support requirements that are summarized next.

Left: A long-duration balloon (LDB) is prepared for launch at the LDB facility on the McMurdo Ice Shelf. The Balloon-borne Large-Aperature Submillimeter Telescope (BLAST) project examined star formations. Photo by James Pappas.

	Advisory Studies					NSF Big Ideas						
Polar Research, Education, and Outreach Drivers	Blue Ribbon Panel (2012)[3]	NRC: Arctic in the Anthropocene (2014)[13]	NSF AC GEO: Dynamic Earth NSF (2014)[2]	NRC: Antarctic & Southern Ocean (2015)[12]	OSTP: Arctic Research Plan (2016)[16]	Understanding the Rules of Life	NSF INCLUDES	Mid-scale Research Infrastructure	Windows on the Universe	Navigating the New Arctic	Harnessing the Data Revolution	Growing Convergent Research
Evolving polar biota		●		●	●	●	●			●	●	●
Arctic environmental change and socioeconomics		●	●				●	●		●	●	●
Globalization - Arctic interactions		●					●	●		●	●	●
Polar connections to global weather		●			●		●	●		●	●	●
Changing land and sea ice level		●	●	●	●		●			●	●	●
Polar ice and global biogeochemical cycles		●	●	●			●	●		●	●	●
Implications of changing permafrost		●					●	●		●		
Polar observation strategies	●	●	●		●		●	●		●	●	●
Nature and origins of the Universe	●		●	●			●	●	●		●	●
Space weather and its impacts	●		●				●	●			●	●

Table 1: OPP research and research support priorities in the left column map to the references where they are discussed.



INFRASTRUCTURE AND LOGISTICS

Research infrastructure and logistics are subject to a number of differing circumstances in the Arctic and Antarctic, including geography, accessibility, and governance, but are critical to the progress of science in both regions. For the Antarctic, OPP acts as the single-point administrator of the U.S. research presence.[8] For the Arctic, where over 4 million people live and which includes the sovereign territory of five nations (including Alaska and surrounding waters for the U.S.), responsibilities and options for research support are more dispersed. OPP operates facilities and provides logistics support in both polar regions with the assistance of private sector logistics contracts as well as cost-reimbursed services from other Federal partners such as the Department of Defense. In addition, OPP frequently leverages its capabilities with international partners to expand the scientific reach of the U.S. research community.

Established Arctic Infrastructure

Arctic infrastructure supported by OPP consists of permanent field stations at Summit Station (Greenland) and Toolik Field Station (Alaska), facilities in Utqiaġvik (Alaska) and Thule Air Base (Greenland), as well as many temporary field camps and access to ships. This includes Long-Term Ecological Research (LTER) sites at Toolik Lake and the newly established Beaufort Lagoon Ecosystem LTER based in Utqiaġvik that are part of the global NSF LTER network. These resources are managed through a

Left: Scientific divers, Chuck Amsler (left in red) and Sabrina Heiser (right in black) enter the water from the Rigil, a Rigid Hull Inflatable Boat (RHIB) used at Palmer Station, Antarctica. Photo by Maggie Amsler.

variety of arrangements with the academic and local communities, interagency and international partners.

Arctic ship-board research can be conducted in the Arctic Ocean and surrounding seas from the 2014-commissioned research vessel (R/V) Sikuliaq, the USCG icebreaker Healy, various international platforms based on cooperative or collaborative arrangements, or contracted private vessels. R/V Sikuliaq is a part of the University-National Oceanographic Laboratory System (UNOLS) as well as the Arctic Research Icebreaker Consortium (ARICE), which consists of 12 European countries, Canada, and the United States. ARICE complements existing opportunities regularly exercised by OPP for U.S. scientists to participate in Arctic Ocean research and international collaborations using foreign vessels. OPP supports the research, technical support and science infrastructure on the USCGC Healy, a medium icebreaker capable of transiting to the North Pole. Ship-time onboard the USCGC Healy is scheduled in parallel with the UNOLS ship-time request process and utilized by NSF and other federal agencies. At this time there are no major, near-term, changes expected for Arctic marine research platforms and OPP should continue to coordinate with NSF's Ocean Sciences Division and other nations to provide the most cost-effective support for marine science in the Arctic.

Antarctic Infrastructure

In Antarctica, NSF is mandated to support three year-round stations on the continent. McMurdo, Palmer and the Amundsen-Scott South Pole stations support research locally and serve as hubs from which a large number of temporary camps on the continent and on islands near the Antarctic Peninsula and elsewhere are supported. The ARSV *Laurence M. Gould* supports logistics and science in the Peninsula region. The R/V *Nathaniel B. Palmer*, supports science throughout the Southern Ocean. Smaller vessels, including two Rigid Hull Inflatable Boats (RHIBs), enable a working radius of up to 20 – 25 miles from Palmer Station. In addition, OPP supports the Palmer marine LTER and the McMurdo Dry Valleys LTER sites in Antarctica.

Antarctic Infrastructure and Logistics Review

Approximately every 10-15 years, NSF has spearheaded an external review of its management of the support of the USAP. The most recent (2012) effort culminated in a Blue Ribbon Panel (BRP) report[3] warning that rising infrastructure and logistics costs would come at the expense of science unless the program tackled inefficiencies. OPP has made headway in addressing recommendations to curb costs, improve safety and enhance science support. For example, the establishment of regular traverse to supply fuel to South Pole Station significantly reduced costs and freed LC-130 aircraft support for science elsewhere on the continent. Another example is the installation of a boat ramp and dock for small boat operations at Palmer station. This has improved safety and allowed for the acquisition of the RHIBs, which extended the scientific reach from Palmer station.

The Antarctic Infrastructure Modernization for Science (AIMS), a project catalyzed by the BRP recommendations, is consolidating resources, co-locating functions, streamlining logistics, and reducing energy consumption at McMurdo Station, the primary hub for U.S. science initiatives in Antarctica. The operational efficiencies that AIMS will provide to the USAP are needed to ensure that McMurdo remains a viable platform for supporting world-class science for the next 35 to 50 years. The AIMS expected completion date is 2027, with the work being sequentially phased-in to ensure continuous functionality and support of science throughout construction.

An additional BRP recommendation was to establish a USAP Capital Investment Plan.[3] This is a systematic and proactive approach needed for OPP to maintain, sustain, and replace USAP infrastructure and capital resources. The AC OPP recommends that OPP continue to consult closely with the research community to support a better understanding of the decision-making processes and trade-offs involved.

The BRP also recommended that the U.S. polar ocean fleet (icebreakers, polar research vessels, mid-sized and smaller vessels) be upgraded to support science, logistics and national security in both polar regions over the long term.[3] The two USAP research vessels (ARSV *Laurence M. Gould* and R/V *Nathaniel B. Palmer*), are approaching end-of-service-life. A sub-committee of the AC OPP has reviewed and assessed the science mission requirements and operational capabilities for replacement of Antarctic research vessels. Their report, Report of the Ad Hoc Subcommittee on theU.S. Antarctic Program's Research Vessel Procurement,[21] was delivered fall of 2019.

Above: The National Science Foundation's (NSF) Harnessing the Data Revolution (HDR) Big Idea is a national-scale activity to enable new modes of data-driven discovery that will allow new fundamental questions to be asked and answered at the frontiers of sciences and engineering. https://www.nsf.gov/cise/harnessingdata/.

Safety

The polar regions are unforgiving, remote locations with extreme weather and harsh environments. Safety has always been a top priority for all researchers, and safety considerations drive the need for the reliable infrastructure and logistics discussed above. AC OPP strongly encourages OPP efforts to facilitate a safe working environment through activities such as hands-on field safety training programs as well as recognition of the NSF-wide grant terms and conditions entitled "*Notification Requirements Regarding Sexual Harassment, Other Forms of Harassment, or Sexual Assault.*"[22]

DATA AND CYBERINFRASTRUCTURE

Increasingly, polar scientists engage in data-intensive science, data management, long-term data access and storage, and complex modeling activities. These endeavors require significant support for advances in computational capabilities and data management, including data archiving and accessibility. "Data" refers to observational, experimental, and model-generated data. Simulation capabilities now routinely generate tera- or petabytes of model diagnostic data. The rapid developments underway in smart sensor technology, miniaturization, autonomous sampling approaches, bioinformatics, and data communication techniques promise a substantial increase in data quantity and quality from both the Arctic and Antarctic. Polar regions face severe bandwidth limitations that currently inhibit the ability to deliver data in near-real time. Enhancing bandwidth offers the possiblility low-latency data delivery as well as reducing the number of personnel in the field. Improvements in cyberinfrastructure and data-intensive exploratory tools are needed to provide novel opportunities to create knowledge in support of societal decision-making. AC OPP advises that OPP focus on the following three cyberinfrastructure and data science areas:

Data Utilization

Optimal utilization of data in the modern context requires that it be clearly and logically organized with active data archiving capabilities that permit analyses, visualization, and manipulation in the cloud. The shifting paradigm from "Data as a Service" to ready-to-use analytical tools, known as "Analysis as a Service" or "Science as a Service," is currently beyond the capability of NSF's major polar data centers.[23] The research community will benefit from strategies for an enhanced platform for Big Data archival, and more importantly, Big Data discovery through emerging tools of data analytics (including Machine Learning and Artificial Intelligence).[23] New resources and applications could also make Big Data and traditional data sets accessible to and discoverable by the general public as well - much like Google Earth has opened a new world to both researchers and the public. The FAIR (Findable, Accessible, Interoperable, Reusable) Data Principles[25] of data sharing provide an overarching framework of data access policies in order to maximize the data's utility and enhance scientific innovation and transparency.

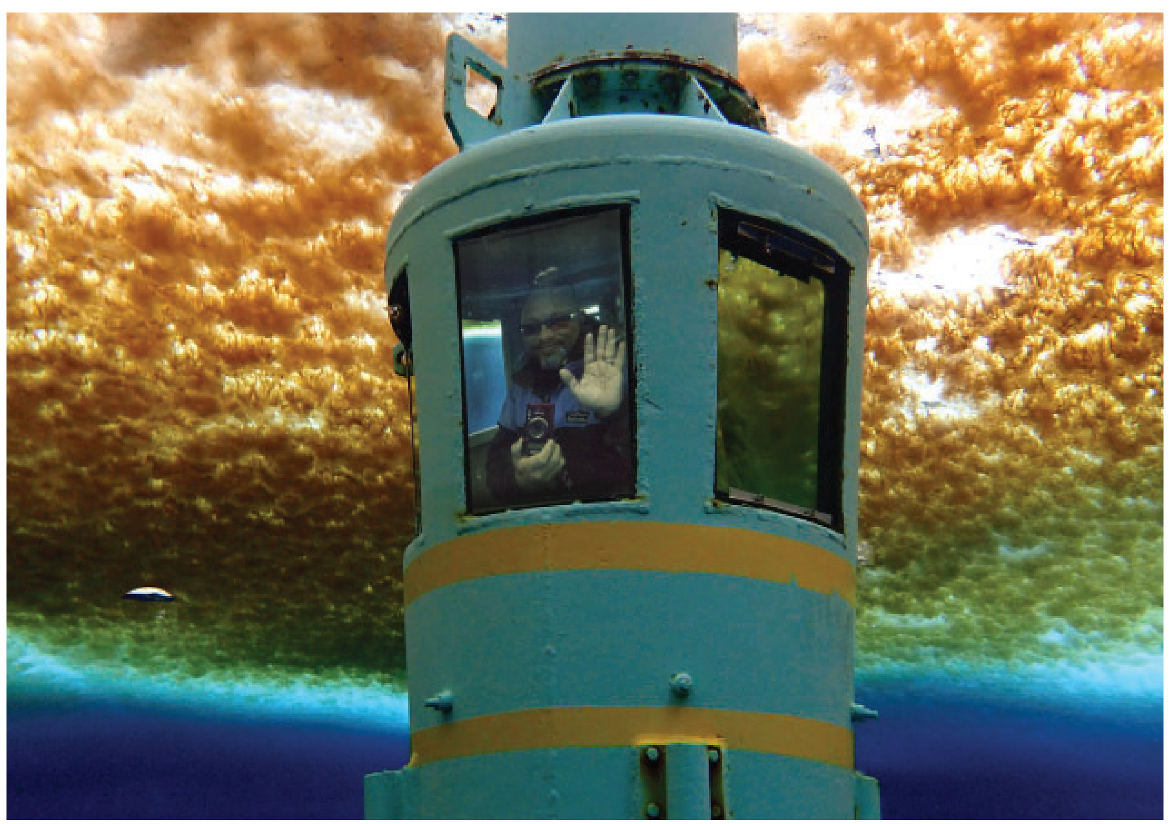
Securing Sensitive Human Data

As polar science incorporates human dimensions, polar relevant data centers need to have necessary protocols in place to allow appropriate dimensions of human data to be queried and integrated while other dimensions, such as identifying characteristics or sensitive information, remain secure. Allowing access while protecting sensitive data presents complexities. AC OPP advises that OPP continue to build on innovative data protocols for this purpose that Arctic researchers working with local communities have pioneered.

Simulation-Based Science

Simulation-based science can faciliate studying complex systems and natural phenomena that are too expensive, too dangerous, or impossible to study at scale by direct experimentation or observation. Key to advancing polar research are numerical models that permit hypothesis testing, optimization of observational strategies and predictions of dynamic processes pertinent to coupled earth systems (see Research Drivers). By their nature, modeling efforts tend to extend beyond the capabilities of single researchers and require convergent research and education approaches.

This simulation-based science encompasses the disciplines of applied mathematics, numerical analysis, statistics, computer science, scientific visualization, targeting the development of algorithms and software that take full advantage of the rapid growth in extreme-scale computing, the data revolution, and the increased attention to data-driven discovery.[26,27] AC OPP advises that OPP enhance engagement with the emergent Computational Science and Engineering fields to provide expertise and focus on the innovation, integration, and convergence of knowledge and methodologies from all of these disciplines. OPP will likely need to extend support beyond that for data centers and their investigators to include high-risk, innovative research foci as well as coordinated community-wide strategic visioning. The breadth of the community interests and needs would be best served by a dedicated program officer in OPP who can coordinate with efforts across NSF.



EDUCATION, DIVERSITY, AND INCLUSION

Education and outreach are fundamental components of NSF's mission and vision. OPP contributes to development of the next generation STEM workforce and public engagement in science and science support through a variety of formal and informal programs directed at age groups ranging from kindergarten through life-long learners.[6] The Advisory Committee believes that the community has been well served by the activities described below. However, to nurture a more diverse and capable future research workforce, OPP should consider undertaking a formal review of its investments across K-12, undergraduate, graduate, and post-graduate education efforts, as well as informal education settings, and explore possible new approaches to achieving those aims.

K-12 and Informal Learning Venues

The long-standing fascination of the Arctic and Antarctic provides unique opportunities for OPP to promote engagement in science on behalf of all of NSF through both formal and informal settings. OPP supports international diplomacy through STEM capacity development programs such as the Joint Science Education Project (JSEP)[28] in Greenland and the Joint Antarctic School Expedition (JASE)[29] in Chile. U.S. students participating in these programs gain first-hand experience with science and collaborate with students from Greenland, Denmark, and Chile during their studies. PolarTREC (Teachers and Researchers Exploring and Collaborating)[30] supports K-12 teachers to spend two to six weeks at polar research sites collaborating with scientific teams and connecting with students and the public via online media.

Left, top: Joint Science Education Project (JSEP) students drilling on the Greenland ice sheet. Photo

Left, bottom: Author Greg Neri waves from inside the Observation Tube, located under the annual sea ice near McMurdo Station. Neri was a National Science Foundation Antarctic Artist and Writer participant visiting Antarctica to research a children's novel about polar science. Photo by Kristen Carlson.

They also develop outreach materials and lesson plans based on the research undertaken that are shared in classroom settings, after-school programs, museums and other informal settings. The Antarctic Artists and Writers Program[30] provides opportunities for scholars in the humanities (fine arts and liberal arts) to work in Antarctica and the Southern Ocean. This program reaches a number of informal education venues and is specifically designed to increase the public's understanding and appreciation of both the Antarctic region and human endeavors on the southernmost continent.

For the past five years, OPP has collaborated with the NSF Directorate for Education and Human Resources (EHR) to encourage proposals to EHR programs for undergraduate, K-12 and informal education. This collaboration is announced via an annual Dear Colleague Letter to bring attention to three programs: Improving Undergraduate STEM Education (IUSE)[32] Discovery Research K-12 (DRK-12)[33] and Advancing Informal STEM Learning (AISL).[34] OPP assists with the merit review process, assesses logistics as needed, and funds or co-funds proposals recommended for an award. The OPP Advisory Committee notes that this has been a successful approach and strongly encourages its continuation.

Undergraduate and Graduate Education

The next generation of the research workforce can be enhanced by expanding OPP support of NSF's Research Experience for Undergraduates (REU) Program[35] and the Graduate Research Internship Program (GRIP).[36] The REUs offer opportunities for exposing undergraduates to the excitement of scientific research, provide realistic training opportunities, and expose them to novel career possibilities. GRIP enables NSF-funded graduate students to intern with host research mentors at federal facilities and national laboratories. These internships increase expertise in critical STEM areas, enhance professional skills, develop broad professional networks, prepare interns for a wide array of career options, and encourage collaborations between NSF and hosting agencies. The sponsor agencies benefit by engaging GRIP fellows in mission-critical projects and by helping develop a highly skilled U.S. workforce in areas of national need. Additionally, OPP should consider expanding upon existing training opportunities/programs for early career scientists that successfully introduce participants to polar science under realistic field conditions and provide opportunities to understand and appreciate the complexities and logistical challenges of working in the polar environment.

Supporting Diverse Research Communities

The AC OPP advises that OPP continue efforts to enhance polar research community diversity. OPP should continue to engage with NSF's INCLUDES (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science). OPP's Arctic research portfolio should continue to provide unique opportunities to encourage Alaskan Native students to pursue career pathways in science and engineering. This emphasis is particularly critical because Indigenous communities will confront novel opportunities and challenges due to the changing Arctic environment which should be addressed with and by the people affected. Moreover, these communities will encounter rapidly evolving technologies that will shape their lives as workers and alter the socio-economic structure of their communities. As one such example toward this objective, OPP supports the Arctic Indigenous Scholars activity,[37] which is led by the Arctic Research Consortium of the U.S. (ARCUS) and the Inuit Circumpolar Council (ICC), Alaska. This activity builds on NSF's investments in Indigenous scholars and supports Indigenous communities to educate and inform scientists, policy- and decision-makers regarding issues of concern pertinent to Arctic communities, such as food security, hunting and fishing rights, community resilience, climate change, biodiversity, and technological impacts.

The AC OPP notes that the Interagency Arctic Research Policy Committee (IARPC) has recently revised and adopted updated Principles for Conducting Research in the Arctic,[38] which are guidelines for conducting responsible and ethical research including engagement with Arctic Indigenous people and residents. To take better advantage of this effort, the AC OPP urges OPP to consider how to better foster understanding and implementation of these principles for the research it sponsors in the Arctic.

SYNERGISTIC PARTNERSHIPS AND COLLABORATIONS

U.S. Agency Partnerships

NSF maintains partnerships across many federal agencies. OPP coordinates closely with the Department of State, Office of Science and Technology Policy and National Security Council for matters of diplomacy and geopolitics in both polar regions. In addition, the Department of Energy (DOE), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), and the Department of Defense's (DoD) Cold Regions Research and Engineering Laboratory (CRREL), Office of Naval Research (ONR), U.S. Arctic Research Commission (USARC) and the National Academies are among the federal and advisory agencies/bodies that have sponsored or advised on research in the polar regions in collaboration with, or supported through, NSF's logistical efforts. In order to promote world leading polar research and serve societally important objectives, it will no doubt remain critically important for OPP will to coordinate and collaborate with these and other federal agencies/bodies concerned with polar research for the foreseeable future.

International Collaborations

Polar regions are best, and sometimes must be, studied and accessed via international collaborations. Such partnerships are key to enabling support of complex and remote field work in both regions. OPP has a well established and extensive track record of productive international collaboration. For example, as of 2014, approximately 80% of OPP awards support U.S. scientists conducting research with international contributions. In addition to supporting collaborative scientific research, OPP engages in *quid pro quo* exchanges by which logistical resources are exchanged with those of other countries. OPP's environmental stewardship responsibilities entail international exchanges of scientific knowledge, data, and recommendations that address the management of polar ecosystems. AC OPP advises that OPP continue its efforts to faciliate international collaboration in science support logistics and research as well as to encourage other nations make more readily accessible their data sets to the broader science community.

International collaboration is becoming an ever more critical foundation for convergent science advances. For example, the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) involves 17 participating countries and over 600 participants, will employ the German research icebreaker *Polarstern* frozen in the sea ice as a central node in an observing network that will drift across the Arctic Ocean during 2019-2020. Interdisciplinary science teams will collaborate to examine interactive oceanic, atmospheric and sea-ice processes over the course of an annual cycle in the Arctic Ocean, filling major data gaps in order to advance predictive weather and climate modeling of the region.

Another example of the benefits of international collaboration is the Greenland Ice Sheet Monitoring Network (GLISN), a collaboratively operated seismic network involving 11 countries from North America, Asia, and Europe. GLISN's high-quality, multi-use seismograph network provides fundamental, long-term data on ice-dynamics such as the glacial earthquakes associated with iceberg fracturing. It allows imaging the static and time-varying properties of the ice-sheet-bedrock interface as well as the underlying crust and lithosphere, which control and respond to ice-sheet dynamics. Data from GLISN contribute to an improved understanding of landslides, tsunamis, and earthquakes, and to monitoring earthquakes and explosions across the Arctic.

In Antarctica, OPP and the United Kingdom's Natural Environment Research Council (NERC) and the British Antarctic Survey are teaming for the International Thwaites Glacier Collaboration (ITGC) to analyze this rapidly changing glacier flowing into the Amundsen Sea. Over a 5-year period, joint teams of U.S. and British scientists and science support personnel will endeavor to reveal the dynamics of Thwaites Glacier, which is believed to be critical to the stability of the West Antarctic Ice Sheet and so global sea-level.

Emerging cutting-edge and transformative research programs in astrophysics and cosmology use the Antarctic continent as an observing platform by partnering hundreds of scientists from North America, Europe, Asia, and Australia. This includes precision measurements of the Cosmic Microwave Background (CMB) and detection

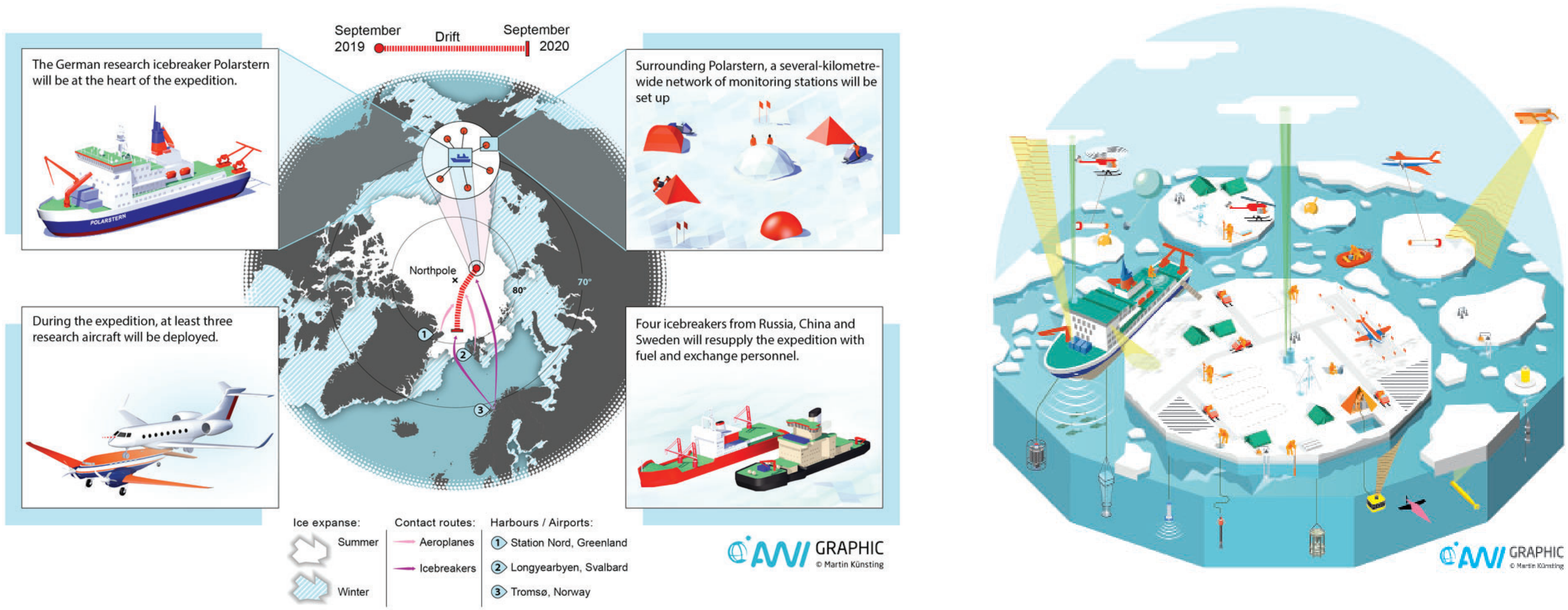


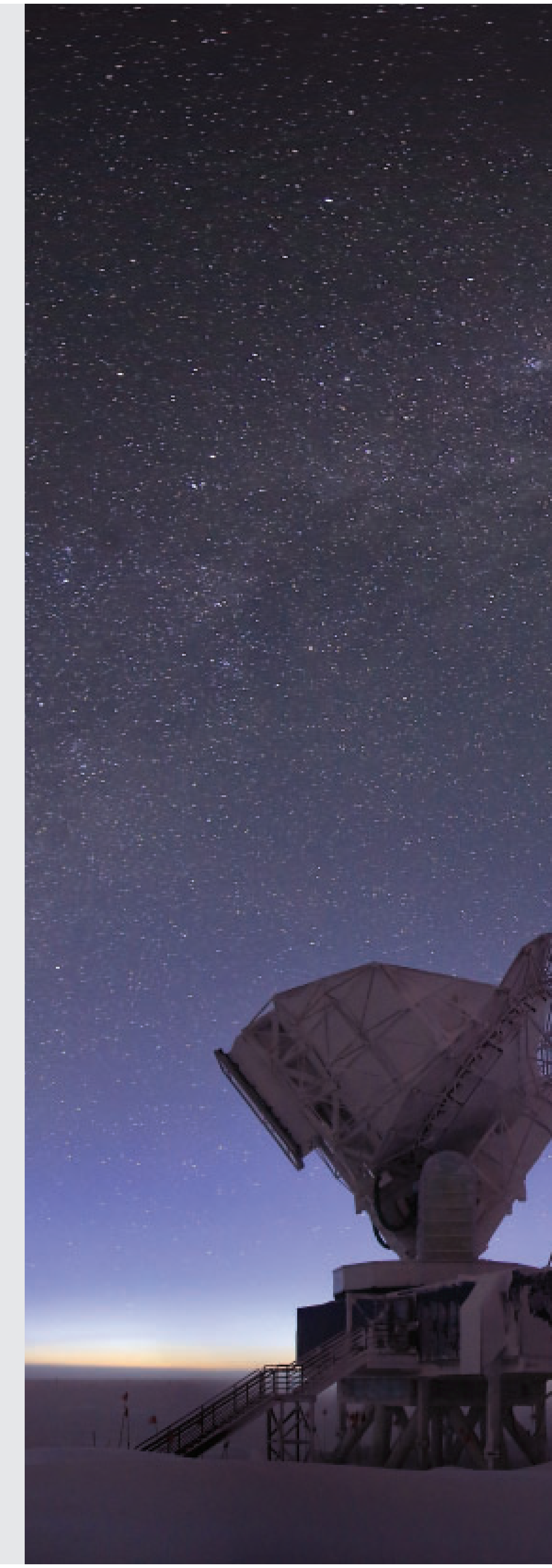
Diagram credit: Alfred Wegner Institute

of high energy neutrinos at South Pole station. Under U.S. leadership, the international community has made numerous remarkable advances including the recent acquisition of the first image of a black hole[39] and first verified source of cosmic rays.[40]

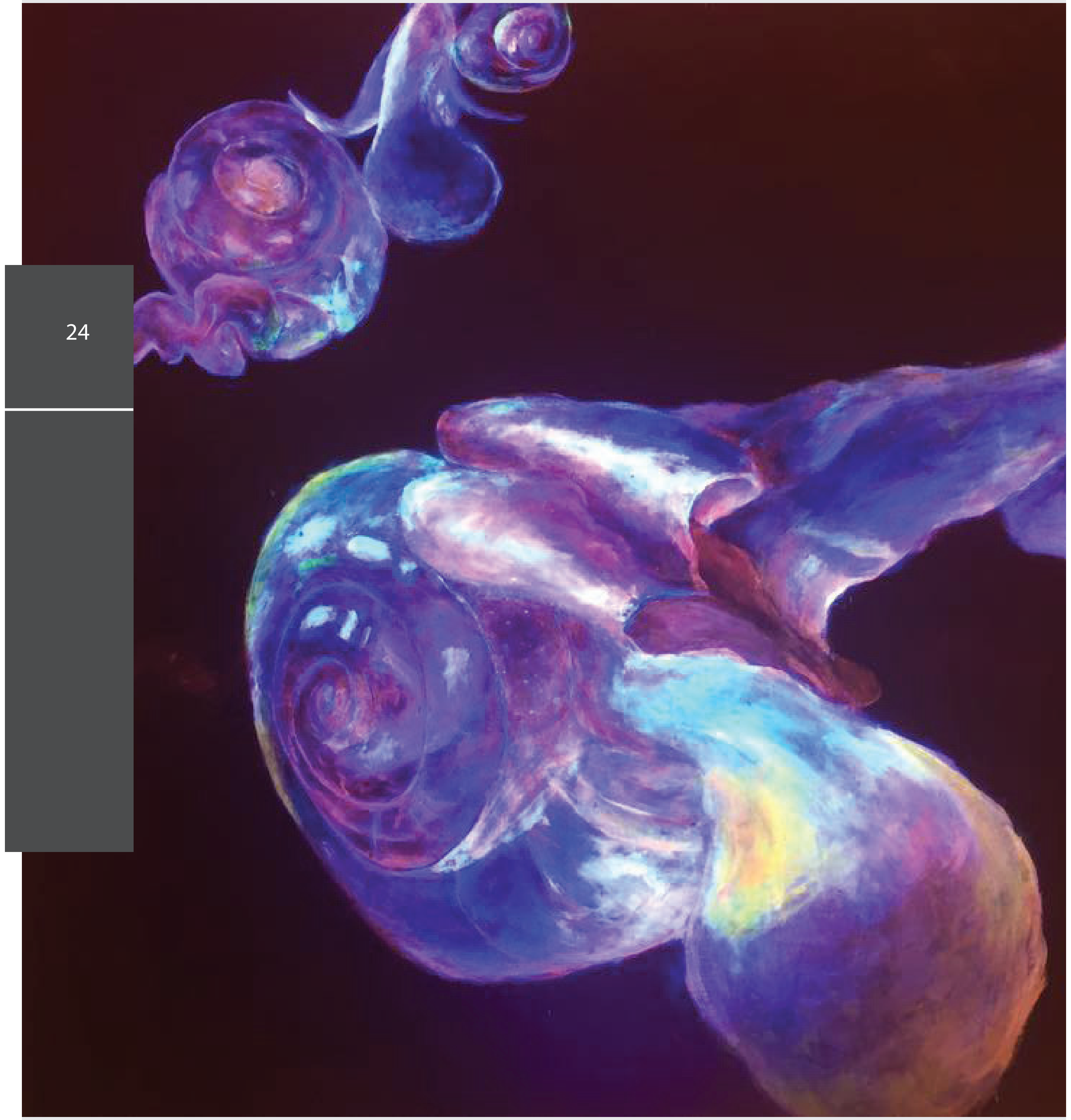
AC OPP strongly endorses continued participation in large-scale, international science efforts that support NSF's Strategic Goals to expand knowledge through investing in ideas, people and infrastructure[6] and OPP's mission to promote scientific discovery and understanding of the polar systems.

CONCLUSION

This exercise to summarize external advice to OPP has strengthened the OPP Advisory Committee's appreciation of the complexity and breadth of the OPP mission as well as the considerable promise of its polar research and support directions. We hope that the reader shares our excitement for the future of OPP stewardship of the polar research enterprise. We conclude by noting that OPP's investments to date in ideas, people, and infrastructure have established critical and fundamental knowledge about the Antarctic and Arctic. In recent years, those investments have propelled a far deeper appreciation of the importance of the connections between polar regions, the global environment, and society. The opportunities and challenges presented by changes underway in polar regions, captured in several of the priority research drivers, are becoming ever more critcial to our nation's economy, security, and well-being. At the same time, it is clear that we still have much to discover about and from our polar regions. Moreover, polar research has and will continue to lead to technological innovation applicable elsewhere, promote the development of the Nation's STEM workforce and enhance the capacity of its citizenry to understand and be inspired by nature's processes and their influence on society.



Right: The Geographical South Pole hosts some unique astronomical experiments, such as the 10m South Pole Telescope (left), the IceCube Neutrino Detector (right) and experiments studying polar lights on various station buildings (middle). Photo by Dr. Daniel Michalik.



APPENDIX I: WORKS CITED

1. Advisory Committee Charter, Advisory Committee for Polar Programs National Science Foundation.
https://www.nsf.gov/geo/opp/opp_advisory/1130_OPPCharter_3_14_17.pdf. Outlines the scope of work, cost, schedule and reporting structure of the Advisory Committee and authorizes related Advisory Committee actives.

2. NSF Advisory Committee to Geosciences Directorate (2015) *Dynamic Earth: Geo Imperatives & Frontiers 2015-2020*.
https://www.nsf.gov/geo/acgeo/geovision/nsf_acgeo_dynamic-earth-2015-20.pdf. The Advisory Committee to Geosciences created these strategic planning recommendations for the NSF Geosciences Directorate.

3. U.S. Antarctic Program Blue Ribbon Panel (2012) *More and Better Science in Antarctica through Increased Logistical Eff ectiveness*. https://www.nsf.gov/geo/opp/usap_special_review/usap_brp/rpt/antarctica_07232012.pdf.
Commissioned to assess the logistics needed to support Antarctic science for the next 30-50 years. Findings included 10 top priority recommendations and 83 actionable items.

4. National Science Foundation (2017) *10 Big Ideas for Future NSF Investments*.
https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf.
Building on the NSF Strategic Plan, these ideas are currently driving NSF's strategic investments to advance the frontiers of research across the agency.

Left: Antarctic Artist and Writer Lily Simonson's *Sea Butterfly Upwelling* (*Limacina Antarctica*), 2016. Oil and acrylic on canvas, 48 x 60 inches.

5. Advisory Committee for Polar Programs Website: https://www.nsf.gov/geo/opp/advisory.jsp.

6. National Science Foundation (2018). *Building the Future Investing in Discovery and Innovation: NSF Strategic Plan for Fiscal Years (FY) 2018-2022*. https://www.nsf.gov/pubs/2018/nsf18045/nsf18045.pdf.
The plan contains three strategic goals:

1. Expand knowledge in science, engineering, and learning
2. Advance the capability of the Nation to meet current and future challenges
3. Enhance NSF's performance of its mission

7. Advisory Committee to Polar Programs (2013). *Recommendations for Polar Programs: NSF Advisory Committee for Polar Programs June 2013*. https://www.nsf.gov/geo/opp/documents/Recommendations%20for%20Polar%20Programs%20-%20June%202013.pdf.
Outlines overarching principals for polar research, which guide Polar Program investments.

8. U.S. Presidential Memorandum 6646 (1982). https://www.nsf.gov/geo/opp/ant/memo_6646.jsp.
This memorandum authorizes the mission of the U.S. Antarctic Program and identifies NSF as the single point manager for the United States national program in Antarctica.

9. Arctic Research and Policy Act of 1984. https://www.gpo.gov/fdsys/pkg/STATUTE-98/pdf/STATUTE-98-Pg1242.pdf (amended 1990) https://www.gpo.gov/fdsys/pkg/STATUTE-104/pdf/STATUTE-104-Pg3125.pdf.
This Act lays the foundations for the U.S. Arctic Research Commission (USARC) and details actions NSF takes when conducting science in the polar regions.

10. Antarctic Treaty System: https://www.ats.aq.
This website hosts documentation, including the Antarctic Treaty, related to the Antarctic Treaty System.

11. Arctic Council (2018) A*greement on Enhancing International Arctic Scientific Cooperation*. https://oaarchive.arctic-council.org/handle/11374/1916.
The eight Parties of the Arctic Council have agreed "…to enhance cooperation in Scientific Activities in order to increase effectiveness and efficiency in the development of scientific knowledge about the Arctic."

12. National Research Council (2015) *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research*. https://www.nap.edu/read/21741/chapter/1.
Commissioned to develop community guidance on priorities and strategic steps forward for Antarctic research, based on the status of the USAP. Findings include maintaining current core programs supporting basic research, three high level strategic priorities and five foundational elements required to support and facilitate the research recommendations.
High level strategic priorities:

1. Changing Antarctic Ice Sheets Initiative
2. Decoding the Genomic and Transcriptomic Bases of Biological Adaptation and Response Across Antarctic Organisms and Ecosystems
3. A Next-Generation Cosmic Microwave Background Program

Foundational Elements required to support and facilitate the research recommendations:

1. Critical Infrastructure and Logistical Support
2. Coordination and Collaboration Opportunities
3. Data Management
4. Education and Public Outreach

13. National Research Council (2014) *The Arctic in the Anthropocene: Emerging Research Questions*. https://www.nap.edu/read/18726/chapter/1.
Builds on existing science and present emerging research questions that are organized within Evolving Arctic, Hidden Arctic, Connected Arctic, Managed Arctic and Undetermined Arctic. Six additional challenges are described that if addressed will increase the ability to address the emerging research questions.

14. SCAR Horizon Scan (2014) https://www.scar.org/about-us/horizon-scan/overview/.

Antarctic scientists, program managers, policy makers, decision makers and early-career scientists identified 80 of the highest-priority, scientific questions about Antarctica and the Southern Ocean to be research priorities in the following two decades. These questions were then distilled into “Six Priorities for Antarctic Science.”

1. Define the global reach of the Antarctic atmosphere and Southern Ocean
2. Understand how, where and why ice sheets lose mass
3. Reveal Antarctica’s history
4. Learn how Antarctic life evolved and survived
5. Observe space and the Universe
6. Recognize and mitigate human influences

15. ICARP III Report (2016) *Integrating Arctic research a Roadmap for the Future: 3rd International Conference on Arctic Research Planning*. https://icarp.iasc.info/images/articles/downloads/ICARPIII_Final_Report.pdf.
This report identified three overarching Arctic research priorities for the next decade, recommendations for coordination, co-production of knowledge and who should be informed as the Arctic changes. Research Priorities include:

1. Understanding the role of the Arctic in the global system
2. Predicting future climate dynamics and ecosystem responses
3. Improving the understanding of the vulnerability and resilience of Arctic environments and societies.

16. Office of Science and Technology Policy (2016) *Arctic Research Plan FY2017-2021*. https://www.iarpccollaborations.org/uploads/cms/documents/iarpc_arctic_research_plan_2017-2021.pdf.
This five-year plan outlines nine research goals:

1. Enhance Understanding of Health Determinants and Improve the Well-being of Arctic Residents.
2. Advance Process and System Understanding of the Changing Arctic Atmospheric Composition and Dynamics and the Resulting Changes to Surface Energy Budgets
3. Enhance Understanding and Improve Predictions of the Changing Arctic Sea Ice Cover
4. Increase Understanding of the Structure and Function of Arctic Marine Ecosystems and Their Role in the Climate System and Advance Predictive Capabilities
5. Understand and Project the Mass Balance of Glaciers, Ice Caps, and the Greenland Ice Sheet and Their Consequences for Sea Level Rise
6. Advance Understanding of Processes Controlling Permafrost Dynamics and the Impacts on Ecosystems, Infrastructure, and Climate Feedbacks
7. Advance an Integrated, Landscape-scale Understanding of Arctic Terrestrial and Freshwater Ecosystems and the Potential for Future Change
8. Strengthen Coastal Community Resilience and Advance Stewardship of Coastal Natural and Cultural Resources by Engaging in Research Related to the Interconnections of People, Natural, and Built Environments
9. Enhance Frameworks for Environmental Intelligence Gathering, Interpretation, and Application toward Decision Support

17. Arctic Research Consortium of the United States (2018) *Arctic Horizons: Final Report*. Retrieved from: http://arctichorizons.org/final-report.
The input from Arctic research community, Indigenous communities, and stakeholder groups is synthesized into 9 research priorities and 11 recommendations to facilitate the research and additional findings from the multi- and transdisciplinary workshops hosted throughout the Arctic Horizons project.

18. National Research Council (2014) *Linkages Between Arctic Warming and Mid-Latitude Weather Patterns: Summary of a workshop*. https://www.nap.edu/read/18727/chapter/1.
Reports on the findings of the workshop attended by Federal Agency Employees and a variety of Arctic scientists. Future needs and opportunities are categorized into observations, models and grand scheme context.

19. National Research Council (2011) *2020 Vision: An Overview of New Worlds, New Horizons in Astronomy and Astrophysics*. https://www.nap.edu/read/12951/chapter/1.

This decadal study created by and for the Astronomy & Astrophysics community provides ten emerging big questions and recommendations for telescopes, instruments and programs.

20. National Research Council (2012) *Solar and Space Physics: A Science for a Technological Society, The 2013-2022 Decadal Survey in Solar and Space Physics.* https://www.nap.edu/read/18974/chapter/1.
Outlines the four overarching science goals for the Solar and Space Physics communities, guiding principles and programmatic challenges expected during the 2013-2022 decade.

21. Ad Hoc Subcommittee of the AC OPP (2019) *Report of the Ad Hoc Subcommittee on the U.S. Antarctic Program's Research Vessel Procurement*. https://www.nsf.gov/geo/opp/opp_advisory/meeting_docs/may2019/RV%20Subcommittee%20final%20report%2014AUG2019.pdf.
This report reviews and assesses the science mission requirements and operational capabilities for replacement of Antarctic research vessels currently supporting the USAP.

22. National Science Foundation (2018) Term and Condition: *Sexual Harassment, Other Forms of Harassment, or Sexual Assault*. https://www.nsf.gov/od/odi/term_and_condition.jsp.
The new award term and condition for all NSF funded awards, went into effect October 22, 2018. This requires awardee organizations to notify NSF of any findings/determinations of sexual harassment, other forms of harassment, or sexual assault regarding an NSF funded Principal Investigator (PI) or co-PI, or of the placement of the PI or co-PI on administrative leave, or the imposition of any administrative action relating to harassment or sexual assault finding or investigation.

23. Polar Geospatial Center (2013) *Report on Workshop on Cyberinfrastructure for Polar Sciences*. https://www.pgc.umn.edu/files/20 18/05/2013-NSF-Cyberinfrastructure-Report-Final.pdf.
This NSF-supported community workshop report address engagement and connections between computer and polar sciences to facilitate the transmission and integration of data and knowledge. It lays out what can be accomplished in the short term (2–5 years) to support a community-driven design, architecture development and optimization of a polar cyberinfrastructure.

24. National Research Council (2013) *Frontiers in Massive Data Analysis*. https://doi.org/10.17226/18374.
Examines the frontiers of data analysis for mining of massive sets and streams of data, develops a taxonomy of some of the major algorithmic problems arising in massive data analysis, identifies gaps in current practice and theory, and proposes a research agenda to fill those gaps while recognizing the multidisciplinary nature of the underlying scientific endeavors.

25. Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., da Silva Santos, L.B., Bourne, P.E. and Bouwman, J. (2016) *The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data*, 3. Found at: https://doi.org/10.1038/sdata.2016.18.
First formal publication of the FAIR Principles, and including the rationale behind them, and some exemplar implementation in the community.

26. Rüde, U., Willcox, K., McInnes, L.C. and Sterck, H.D. (2018). Research and education in computational science and engineering. *SIAM Review*, 60(3), 707-754. http://doi.org/10.1137/16M1096840.
Report from a community workshop sponsored by the Society for Industrial and Applied Mathematics (SIAM) and the European Exascale Software Initiative (EESI-2); presents challenges, opportunities, and directions for computational science and engineering (CSE) research and education for the next decade in the face of disruptive developments, including the architectural complexity of extreme-scale computing, the data revolution that engulfs the planet, and the specialization required to follow the applications to new frontiers.

27. Office of Science and Technology Policy (2016) *National Strategic Computing Initiative - Strategic Plan, 2016*. https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NSCI%20 Strategic%20Plan.pdf.

Identifies areas where government engagement, in collaboration with industry and academia, is essential in creating the technological capability, computational foundations, and workforce capacity to realize the objectives of the NSCI for a robust and enduring High-Performance Computing ecosystem. Among these objectives are deployment of capable exascale computing, support of coherence in data analytics as well as simulation and modeling, and exploration of new paths and partnerships for future computing architectures and technologies.

28. The Joint Science Education Proejct (JSEP): https://dickey.dartmouth.edu/arctic-environment/programs/jsep-and-jase/program-info/jsep.
NSF supported project run by Dartmouth's Institute of Arctic Studies. Students from U.S. high schools, Dartmouth graduate programs, Greenlandic and Danish schools spend three weeks in Greenland at both the Kangerlaussuaq Science Field School and Summit Camp.

29. The Joint Antarctic School Expedition (JASE): https://dickey.dartmouth.edu/arctic-environment/programs/jsep-and-jase/program-info/jase.
NSF supported project run by Dartmouth's Insitiute of Arctic Studies. Chilean and U.S. students spend time in both Chile and Antarctica to learn and study global scientific issues, polar science, as well as develop relationships.

30. PolarTREC (Teachers and Researchers Exploring and Collaborating): https://www.polartrec.com/.
The nonprofit Arctic Research Constorium of the United States (ARCUS) manages this program. Educators from formal and informal U.S. insitutions spend 2-6 weeks in either the Arctic or Antarctic participating in hands-on field research experiences.

31. Antarctic Artists and Writers Program (AAW): https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503518.
NSF OPP's program that facilitates writing and artistic projects designed to increase the public's understanding and appreciation of the Antarctic and human endeavors on the southernmost continent.

32. Improving Undergraduate STEM Education (IUSE): https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505082.
NSF Directorate for Education and Human Resources (EHR)'s Division of Undergraduate Education (DUE) program's Improving Undergraduate STEM Education (IUSE) solicitation.

33. Discovery Research K-12 (DRK-12): https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=500047.
NSF Directorate for Education and Human Resources (EHR)'s Division of Research on Learning in Formal and Informal Settings (DRL) program's Discovery Research K-12 (DRK-12) solicitation.

34. Advancing Informal STEM Learning (AISL): https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504793.
NSF Directorate for Education and Human Resources (EHR)'s Division of Research on Learning in Formal and Informal Settings (DRL) program's Advancing Informal STEM Learning (AISL) solicitation.

35. Research Experience for Undergraduates (REU) Program: https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517.
NSF-wide opportunity to fund programs offering research experiences to undergraduate students.

36. Graduate Research Internship Program (GRIP): https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505127.
An opportunity funded by the Division of Graduate Education (DGE), which is within NSF's Directorate for Education and Human Resources (EHR).

37. Arctic Indigenous Scholars: https://www.arcus.org/indigenous-scholars.
Led by the Arctic Research Consortium of the U.S. (ARCUS) and the Inuit Circumpolar Council (ICC) Alaska, and supported by the NSF's Division of Arctic Sciences. Creates a space for Indigenous scholars to educate and inform policy- and decision-makers engaged in Arctic issues.

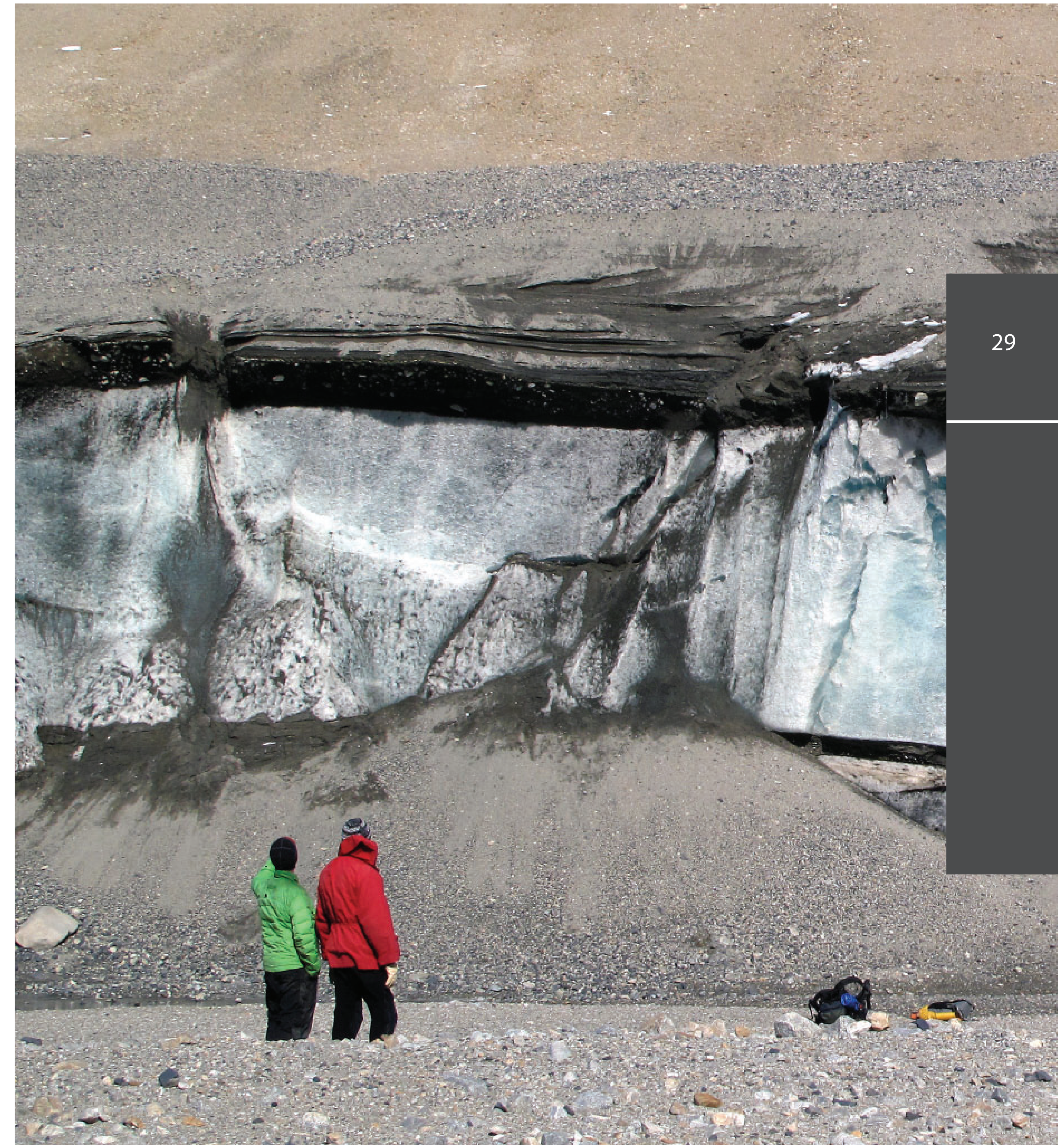
38. IARPC Collaborations (2018) Principles for Conducting Research in the Arctic https://www.iarpccollaborations.org/principles.html.
The core Principles for Conducting Research in the Arctic are:

- Be **Accountable**
- Establish Effective **Communication**
- **Respect** Indigenous Knowledge and Cultures
- Pursue Responsible Environmental **Stewardship**

39. Event Horizon Telescope Collaboration. (2019). First M87 Event Horizon Telescope results. I. The shadow of the supermassive black hole. *Astrophys. J. Lett*, 875, L1. https://iopscience.iop.org/article/10.3847/2041-8213/ab0ec7.
The fi rst images of a black hole were assembled then published in 2019. These images are consistent with predictions of general relativity.

40. IceCube Collaboration. (2018). Neutrino emission from the direction of the blazar TXS 0506+ 056 prior to the IceCube-170922A alert. *Science, 361*(6398), 147-151. Found at: http://doi.org/10.1126/science.aat2890.
The high-energy neutrino dectected by IceCube in 2017, was traced to originate from a blazar. Previously, blazars were understood to be unlikely sources of cosmic rays.

Right: An exposed ice cliff of ancient ice in Garwood Valley, Antarctica. Photo by James O'Connor.



ACKNOWLEDGEMENTS

The AC OPP would like to thank Dr. Kelly K. Falkner, Director of the Office of Polar Programs and the OPP team, for the leadership and momentum needed to move this report forward. In particular, Beverly Walker, OPP Science Assistant and AC OPP liaison, was instrumental in managing and facilitating the work for this report, researching topics as needed, as well as organizing commentary and suggestions coming from the science community, the AC OPP and OPP staff; and Terri Edillon, for her work on graphics, layout, and refinement of the final product as well as assistance with the web platform for communicating with the broader community.

We also thank the members of the polar science community who offered suggestions and comments on this report.

Left: A minke whale exhales air through its blowhole. Photo by Ari Friedlander.

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