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An Advisory Overview for the Office of Polar Programs

ADVISORY COMMITTEE TO THE OFFICE OF POLAR PROGRAMS

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Purpose

The National Science Foundation (NSF) Office of Polar Programs (OPP) provides a critical nexus for the support of our nation's polar research, i.e. research in and about polar regions. Being geographically defined, the purview of the OPP 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 exciting potential for future fundamental explorations and discovery in and about polar regions that is underscored by their relevance to decision-makers. Although geographically remote, polar regions exert important global influences that affect weather and climate, natural resource accessibility, and human socio-economic systems. These global links occur through ocean circulation, spatial and temporal disposition of sea and glacial ice and permafrost, 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.

A variety of existing reports from a number of perspectives are relevant to OPP investments in research and operations. To help inform science funding leadership, other NSF Advisory Committees and additional stakeholders, the Advisory Committee for the Office of Polar Programs (AC OPP)[1] determined the need to develop a higher-level synthesis of the current community-recommended priorities for OPP investments.

To craft this advisory overview, the AC OPP drew from the most current National Research Council (NRC) of the National Academies of Science, Engineering and Medicine (NASEM) reports and interagency and international science planning documents noted in Appendix 1. As OPP is part of NSF's Geosciences Directorate, the AC OPP also reviewed the 2014 planning effort prepared by the Geosciences AC, *Dynamic Earth: GEO Imperatives and Frontiers 2015–2020*[2]. We generally restricted our review to documents that arose via consultation with the research communities and which were produced within the past five years. We also included the 2012 Blue Ribbon Panel Report[3] regarding Antarctic infrastructure and logistics, because it remains highly relevant to long term investments and subsequent advisory reports build on it.

This document summarizes current pressing research drivers in the form of ten key questions. The AC OPP considered how these categories relate to NSF's 10 Big Ideas[4], which are currently guiding NSF strategic investments, and found considerable alignment with the community-based research drivers found in the NRC reports. We 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 partnerships.

This overview is not intended to supplant the in-depth documents upon which we drew; the interested reader is referred to them for fuller details. We hope that we succeeded in providing a useful overview. The Advisory Committee recommends that OPP staff continue to build on and strengthen efforts to make these science and science support objectives broadly known to the polar research community, as well as entrain new expertise toward achieving polar research priorities. As a formal advisory body[1], the OPP AC welcomes community feedback as we endeavor to help OPP and NSF identify areas worthy of future advisory focus[5].

Introduction

NSF's Mission

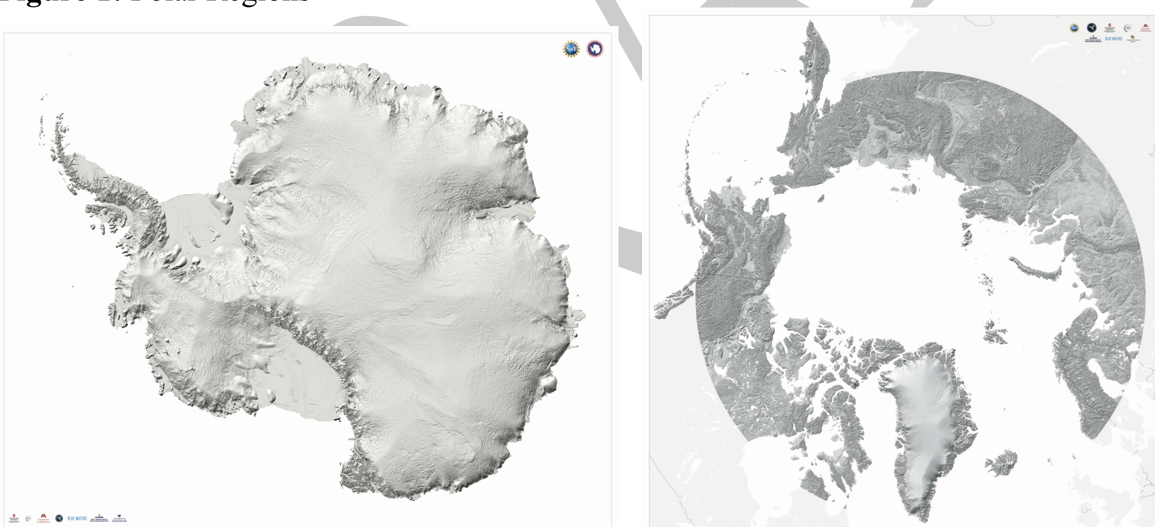
"To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense; and for other purposes." -The National Science Foundation Act 1950

NSF's Vision

"A Nation that is the global leader in research and innovation"

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"*[6]. 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.

Figure 1: Polar Regions



Left side is The Reference Elevation Model of Antarctica (REMA) (https://www.pgc.umn.edu/data/rema/) and right side is the ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/) or digital elevation model (DEM). Both illustrate the unique landscape in which polar scientists work. Figures by PGC using data from the NSF-NGA supported Arctic DEM and REMA projects.

To facilitate polar research on behalf of NSF and other communities, OPP exercises operational responsibilities encompassing infrastructure, logistics, health, safety, environmental stewardship and international collaboration. In the Antarctic, OPP executes the presidential mandate that charges NSF with managing the U.S. Antarctic Program (USAP) on behalf of the nation[7]. In the

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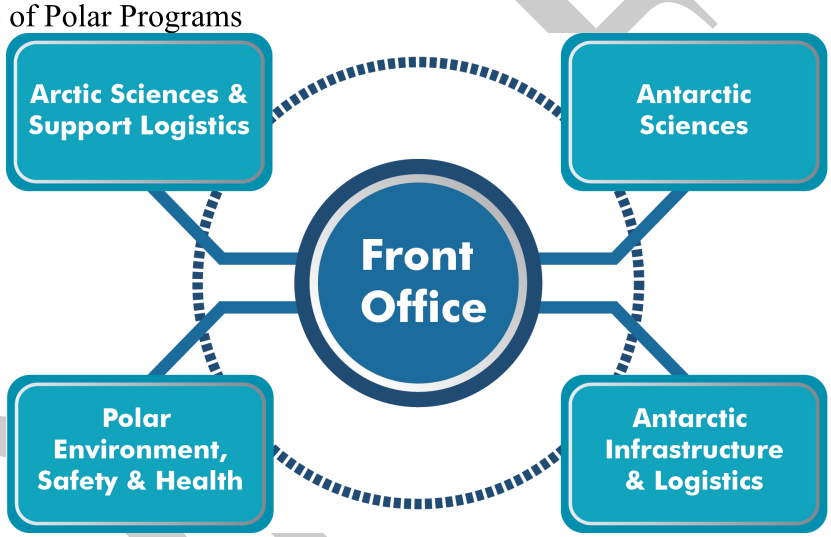
case of the Arctic, the Arctic Research Policy Act[8] names the NSF Director as the chair of the Interagency Arctic Research Policy Committee (IARPC); OPP supports the IARPC chair role and promotes active interagency engagement toward a well-coordinated national Arctic research agenda.

Through participation in U.S. delegations to the Antarctic Treaty System[9] and in activities related to the Arctic Council[10], 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 always been fundamental to international cooperation in the polar regions. The International Geophysical Year in 1957-58 led directly to the formation of the Antarctic Treaty in 1959.[9] In subsequent years, science supported within the Antarctic Treaty System,[9] lead to the negotiation of the Convention for the Conservation of Antarctic Marine Living Resources. Similarly, the Arctic Council grew directly out of the cooperation fostered by the International Arctic Science Committee, which was guided by NSF leadership.

Image 1: Office of Polar Programs



Front Office: Comprises leadership, administrative, budget and IT systems support, education liaison, 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, and assisting in support of facilities in Alaska as well as arranges fro research access and support elsewhere in the Arctic; Contributes a coordinating role for research support on the 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 & Logistics (AIL): Responsible for coordination and oversight of Antarctica 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*, enlisting federal and private support services for the USAP.
Polar Environmental, Safety & Health (PESH): Develops policy for and oversees environmental stewardship, safety, and health for both polar regions.

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Research Drivers

The OPP Advisory Committee synthesized research themes presented in currently relevant advisory reports (as cited) in the form of ten principle research questions below. Note that these are presented in no particular order and all are important for guiding OPP investments.

How have polar biota evolved in extreme environments and how will these biotas adapt to a changing climate?[4,11,12,13] 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 they provide natural laboratories for studies of organismal response to rapidly changing climate conditions. Understanding the adjustments of organisms and ecosystems to past and current environmental changes will lead to a broader understanding of the evolution, limits, and distribution of life, and thus provide insights for understanding the rules of life. This research will also provide insights on how such adjustments may be accomplished by non-polar organisms and ecosystems.


Photo Credit: Dave Munroe


Photo Credit: Peter Rejeck


Photo Credit: Todd Surovell

How will the decrease in Arctic sea ice and permafrost affect regional and global socio-economic systems? [2,4,12,14,15] Decreased sea-ice could increase accessibility to marine transportation corridors, mineral resources, and new fisheries. Decreased permafrost could increase the levels of greenhouse gases affecting climate and increase engineering demands associated with destabilized coastlines and terrestrial landforms. These changes could also impact the cultures, governance structures, and interactions of Indigenous communities with non-polar societies. The potential for resource development, alternative shipping routes, and unsettled exclusive economic zone claims affects both Arctic and non-Arctic nations.

How are Arctic societies responding to globalization?[4,12,16] Arctic Indigenous people and other Arctic residents are at the forefront of global 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 and local knowledge. Social and natural sciences must be applied to understand such interactions in order to help inform future societal trajectories and 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 and healing; food and energy security; interdisciplinary archaeological

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research that yields data on such things as past climate and ecosystem states as well as human adaptive responses to change; collaborative heritage and linguistic preservation; and ethical research and data management.

What is the connection between the Arctic and global atmospheric weather and climate patterns?[4,12,15,17] Arctic amplification, the disproportionately large warming in the Arctic relative to mid-latitudes, will strengthen as greenhouse gas concentrations increase. How Arctic amplification affects weather patterns over the continental United States and elsewhere remains uncertain and research is needed to address the nature of this linkage, the magnitude of the possible influence on mid-latitude weather relative to non-Arctic factors, the spatial and temporal dimensions of the influence, and the type of weather events most susceptible to Arctic influence.

What are the rates and magnitudes of sea level rise associated with the loss of polar land ice? [2,4,11,13,15] 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 to coastal regions. 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 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 multi-scale, multi-physics grand challenges.

Photo Credit: Vasilli Pentreko

Photo Credit: Laurence C. Smith.

How will reductions in sea ice, glaciers, and ice sheets, affect the global ocean circulation, climate, and the global carbon cycle? [2,4,11,12,14] 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. This freshening alters the vertical stratification of the ocean, affecting the carbon cycle and climate through changes in marine productivity, deep water formation rates, and adjustments in the global overturning ocean circulation. However, the magnitude and rates at which melting and freshening occurs, 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

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communities, and patterns and rates of marine production. Marine community structure and production rates are also affected by ocean acidification, which is enhanced by ice melt and increased concentrations of atmospheric carbon dioxide.

Photo Credit: Chris Linder

Photo Credit: James O'Connor

How do changes in permafrost affect the hydrologic cycle in the Arctic, the carbon cycle and global climate? [2,4,12] 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 large, but uncertain, feedbacks on climate and the global carbon cycle. A reduction in permafrost will also alter freshwater discharge cycles and surface hydrology. These changes may lead to alterations in the productivity and the 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 poorly understood. Moreover, how carbon loss from permafrost will be modified by changes in terrestrial vegetation and primary production is unresolved. Research is needed to allow better incorporation of permafrost-related processes into climate system models in order to improve the predictive capability of these models.

How does society more efficiently observe and measure the polar regions?[2,4,15] 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 do so 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, timely data provides an "early warning system" of abrupt or hazardous changes, which permit informed societal responses. Establishing these networks entails developing new instruments and autonomous sensors for fixed and/or mobile platforms, innovative data retrieval techniques, and robust cyberinfrastructure. 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 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.

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What processes govern the evolution, the structure, and the fate of the universe (astrophysics and cosmology)?[2,3,4,11,18] 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 must continue to be, vital in supporting new advances in the era of multi-messenger astrophysics.

Photo Credit: Ben Adkinson

Photo Credit: James Pappas

How does space weather affect human life and the technological systems upon which society depends?[2,3,4,19] 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 is 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 Divison's *Solar, Heliospheric, and Interplanetary Environment (SHINE)* program and interagency collaborations with DOD, NASA, and NOAA and with private industry.

All of these research priorities were synthesized from current reports based on input from the polar science community. 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. This is demonstrated in Table 1 by the considerable cross-mapping of OPP priority research drivers with the NSF 10 Big Ideas. Table 1 also includes process/support priorities that are summarized next.

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Table 1: Summary of Priorities

	NRC: Antarctic and Southern Ocean (2015)	NRC: Arctic in the Anthropocene (2014)	NRC: Astronomy & Astrophysics (2011)	NRC: Solar & Space Physics (2012)	Blue Ribbon Panel (2012)	Dynamic Earth. NSF GEO AC (2014)	Rules of Life	INCULDES	Midscale Research Infrastructure	Windows on the Universe	Navigating the New Arctic	Harnessing the Data Revolution	Growing Convergent Research
Polar Biota	X	X					X	X			X	X	X
Arctic sea ice and socio-economic systems		X				X	X	X	X		X	X	X
Arctic Reponse to Globalization		X						X	X		X	X	X
Connection with Arctic and global weather		X						X	X		X	X	X
Polar land ice loss and sea level rise	X	X				X		X			X	X	X
Polar ice changes and global ocean ciruclation, climate & carbon cycles	X	X				X		X	X		X	X	X
Permafrost: Greenhouse gas Influx		X						X	X		X		
Efficient observations and measurements of the polar regions		X			X	X		X	X		X	X	X
Evolution and structure of the universe	X		X		X	X		X	X	X		X	X
Space weather, human life and technology				X	X	X		X	X			X	X
Capital Infrastructure Investments	**X**	**X**	**X**		**X**	**X**							**X**
Data & Cyber Infrastructure	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Education & Outreach	**X**	**X**	**X**	**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

Each priority maps to the references where they are discussed. The blue text represents NSF's 10 Big Ideas that are applicable to each of the OPP priorities. The upper priorities are research priorities and bolded priorities (lower) are ancillary drivers, yet equally important to OPP's mission.

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Infrastructure and Logistics

Due to the differences in geopolitical structure, geography, risk variables, and accessibility to the polar regions, scientists use different platforms to accomplish their research. In the Arctic, there is a decentralized approach with a number of established mechanisms to support research where it needs to occur. Infrastructure includes permanent field stations located at Summit Station (Greenland) and Toolik Field Station (Alaska), facilities in Utqiaġvik (Alaska) and Thule Air Base (Greenland), on ships, and at numerous temporary field camps. These facilities are supported by OPP and managed through collaborations with the University of Alaska (Toolik), local communities, international partners, interagency partners, and the principal investigators. OPP should also continue to support agency-wide Long-Term Ecological Research (LTER) sites such as the one at Toolik Lake and the newly established Beaufort Lagoon Ecosystem LTER based in Utqiaġvik, Alaska.

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), consisting of 12 European countries, Canada, and the United States. ARICE complements existing opportunities regularly exercised by the Arctic Sciences Section 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. *Healy* is scheduled in parallel with the UNOLS process and utilized by NSF and other federal agencies. At this time there are no major, near-term, changes expected for Arctic research platforms and OPP should continue to coordinate with NSF'd Oceans Sciences Division and other nations to provide the most cost-effective support for marine science.

Photo Credit: Roger Topp

Photo Credit: Margaret Amsler

In Antarctica, all works is centralized through the OPP-led USAP hubs. These hubs support research at permanent field stations at McMurdo, Palmer and the Amundsen-Scott South Pole stations and temporary camps on the continent and on islands near the peninsula. On the water, R/V *Laurence M. Gould* supports science along the Antarctic Peninsula, R/V *Nathaniel B. Palmer* while capable of science anywhere in the Southern Ocean, primarily supports science in the Ross Sea and in the Southern Ocean between Australia and South America. Smaller scale

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vessels including two Rigid Hull Inflatable Boats (RHIBs), *Rigil* and *Hadar,* which have recently expanded the working range from Palmer Station an additional 20 to 25 miles. In addition to maintaining the USAP infrastructure, OPP should also continue to support the Palmer LTER and the McMurdo Dry Valleys LTER sites in Antarctica.

The 2012 Blue Ribbon Panel (BRP) report[3] predicted that rising infrastructure and logistics costs may come at the expense of science. OPP has made headway in addressing recommendations related to rising costs. For example, the establishment of traverse capabilities to supply fuel to South Pole Station has benefitted the science community through reduced costs and greater LC-130 aircraft support elsewhere on the continent. OPP should continue to address remaining recommendations to address aging USAP infrastructure in a manner that accommodates a healthy science portfolio.

The Antarctic Infrastructure Modernization for Science (AIMS) will consolidate resources, co-locate functions, streamline logistics, and reduce energy consumption at McMurdo Station, the primary hub for U.S. science initiatives in the Antarctic region. Operational efficiencies AIMS will provide to the USAP are needed to ensure McMurdo Station remains a viable platform for supporting world-class science for the next 35 to 50 years. The expected completion date for AIMS is 2027. AIMS is being phased over this time frame to accommodate science priorities.

An additional BRP recommendation was the establishment of an explicit USAP Capital Investment Plan.[3] A systematic and proactive approach is needed for OPP to maintain, sustain and replace USAP infrastructure and capital resources. The OPP Advisory Committee recommends that OPP share developments in this regard with the community to support better understanding and support of decision making and the 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 (R/V *Laurence M. Gould* and R/V *Nathaniel B. Palmer*), serving Antarctic seas, are at their mid-life stage and planning for their replacement or retrofit is needed. A sub-committee of the OPP Advisory Committee is currently reviewing and assessing the science mission requirements and operational capabilities for replacement of Antarctic research vessels with a report expected in the spring of 2019.

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 advances in computational capabilities and data management, including data archiving and accessibility. (Here "data" here refers broadly to observational, experimental and model-generated data.) The explosion in smart sensor technology, miniaturization, autonomous sampling approaches, and data communication techniques promises a cost-effective increase in data quantity and quality from both the Arctic and Antarctic. Simulation capabilities now routinely generate tera or peta bytes of model diagnostic data. When used in conjunction with improvements in cyberinfrastructure and data-intensive exploratory tools, these developments provide novel opportunities to create knowledge in support of societal decision-making. OPP

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must play a leading role in promoting improvements in cyberinfrastructure by focusing on three areas.

First, the optimal utilization of data requires that it be organized clearly and logically, and includes active data archiving that permits analyses, visualization, and manipulation in the cloud. The shifting paradigm from "Data as a Service" to "Analysis as a Service" or "Science as a Service" is currently beyond the capability of NSF's major polar data centers.[20] 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).[20] 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) principles 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.

A second area of focus is on appropriately handling human data. Whether this data falls into the category of Big Data or is obtained through detailed individual collection, 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, remains secure. Developing these capabilities is a complex task. Indeed, Arctic researchers working with local communities have pioneered innovative data protocols that allow for such analysis.

Image credit: James Kurose, NSF

Finally, OPP must continue to support knowledge production through simulation-based science applied to studying complex systems and natural phenomena that are too expensive, too dangerous, or impossible to study by direct experimentation or observation. This encompasses new developments in the disciplines of applied mathematics, numerical analysis, statistics, computer science and 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.[22,23] Computational Science and Engineering is the enterprise that focuses on the innovation, integration and convergence of knowledge and methodologies from all of these disciplines and the relevant domain expertise of the system being studied. Key applications in polar research are numerical models that improve hypothesis testing and predictions of processes pertinent to coupled polar system processes and dynamics, air-sea-ice interactions, high-latitude biogeochemical cycling, ecosystem and

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environmental change, infrastructure development, socio-economics, and the dynamical linkage between polar and extra-polar weather and oceanic processes. By their nature, these investigations are beyond the capabilities of single researchers and require interdisciplinary collaborations engaged in convergent research and education efforts.

It is essential that funding be made available for these critical research areas that extend beyond support of data centers and their investigators. This research should range from high risk innovation to coordinated community-wide strategic envisioning and may be best served beyond a dedicated program officer who can coordinate with efforts across NSF.

Education and Diversity

Education and outreach are fundamental components of NSF's mission and vision, supporting the development of the next generation STEM workforce and educating the general public. OPP contributes to these efforts through a variety of formal and informal programs directed at age groups ranging from kindergarten through life-long learners.[13] 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, informal education settings, undergraduate and graduate education efforts and explore possible new approaches to achieving those aims.

OPP engages with NSF's INCLUDES (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science) program by encouraging the support of minorities in undergraduate and graduate research. OPP's Arctic research portfolio provides unique opportunities to encourage Alaskan Native students to pursue career pathways in science and engineering. This emphasis is particularly critical because the changing Arctic environment implies that Indigenous communities will confront novel opportunities and challenges that are best be addressed 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.[9,11,12]

The next generation of research workforce can be enhanced by expanding the Research Experience for Undergraduates (REU) Program (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517) and the Graduate Research Internship Program (GRIP) (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505127). The REUs offer opportunity for exposing undergraduates to the excitement of scientific research, provides realistic training opportunities, and exposes them to novel career possibilities. GRIP enables NSF-funded graduate students to intern with host research mentors at Federal facilities and national laboratories. Such undertakings encourage collaborations between NSF and these agencies, increase expertise in critical STEM areas, enhance professional skills and networks, and prepare interns for a wide array of career options. 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. OPP should consider expanding training programs, such as the Antarctic Biology Training Program (https://www.usfca.edu/arts-sciences/antarctic-biology-training-program) for early career scientists. This NSF-sponsored program, conducted collaboratively with the Universities of San Francisco and Southern California, has successfully

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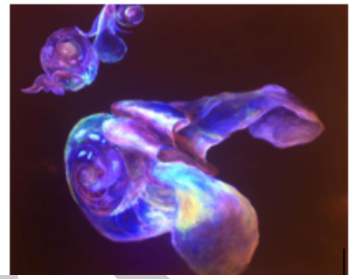
introduced participants to Antarctic science under realistic field conditions, and provided opportunities to understand and appreciate the complexities and logistical challenges of Antarctic science. OPP could consider expanding this program to the Arctic and across other disciplines.

Photo Credit: Lars Poort

Photo Credit: Kristen Carlson



Painting by Lily Simonson

The long-standing fascination of the Arctic and Antarctic provides OPP with unique opportunities to promote public engagement in science on behalf of all of NSF through both formal and informal venues. OPP supports programs such as the Joint Science Education Project (JSEP) (https://www.arcus.org/jsep) in Greenland and the Joint Antarctic School Expedition (JASE) (https://dickey.dartmouth.edu/environment/programs/jase/joint-antarctic-school-expedition-jase-participants) 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. The Antarctic Artists and Writers Program (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503518) provides opportunities for scholars in the humanities (fine arts and liberal arts) to work in Antarctica and the Southern Ocean and is specifically designed to increase the public's understanding and appreciation of the Antarctic and human endeavors on the southernmost continent. PolarTREC (Teachers and Researchers Exploring and Collaborating) (https://www.polartrec.com/) is a program for K-12 teachers to participate in field research in the polar regions to improve their knowledge of polar science and to extend current scientific research beyond the scientific community. PolarTREC teachers spend two to six weeks at polar research sites, collaborating with scientific teams, and connecting with students and the public via online media. Outreach material and lesson plans are created based on the research undertaken, which are then shared throughout a variety of classroom settings, after-school programs, museums, and other informal settings.

For the past five years, OPP has collaborated with the Directorate for Education and Human Resources 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 the three programs, Improving Undergraduate STEM Education (IUSE) (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505082), Discovery Research K-12 (DRK-12) (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=500047) and Advancing Informal STEM Learning (AISL) (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504793). OPP assists with the review process, including the logistics review if 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.

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As an example of diversity, OPP supports the Arctic Indigenous Scholars activity (https://www.arcus.org/indigenous-scholars), which is led by the Arctic Research Consortium of the U.S. (ARCUS) and the Inuit Circumpolar Council, Alaska.[16] This activity builds on NSF's investments in Indigenous scholars and supports Indigenous communities to advance issues of concern pertinent to Arctic communities, such as food security, hunting and fishing rights, community resilience, climate change, biodiversity, and technological impacts. This forum provides opportunities for these scholars to educate and inform scientists, policy- and decision-makers engaged in Arctic issues of Indigenous concern.

Synergistic Partnerships & Collaborations

NSF maintains partnerships across many federal agencies. It contributes directly to national security discussions through its participation in the Department of State's Arctic Policy Committee and other venues. 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) and Office of Naval Research (ONR) are among the federal agencies that have conducted research in the polar regions in collaboration with or supported through NSF's logistical efforts. OPP will need to continue to coordinate and collaborate with other federal agencies concerned with polar research and work with the U.S. Arctic Research Commission (USARC) and the National Academies of Science, Engineering and Medicine (NASEM) to develop strategic research priorities through time.

Polar regions are best, and sometimes must be, studied and accessed via international collaborations. Such partnerships enable support of complex and remote field work in both regions; OPP has long facilitated such collaborations. For example, as of 2014 over 80% of OPP awards supported U.S. scientists conducting research as a member of an international team. In addition to supporting scientific research, OPP engages in *quid pro quo* exchanges in which logistical resources are shared with other countries. There are also international exchanges of scientific knowledge, data, and recommendations that address the management of polar ecosystems, which guides OPP's environmental stewardship responsibilities.

Participation in these international collaborations is often the foundation for multinational, convergent science efforts. For example, the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project in the Arctic, which involves 17 participating countries, will use the German-owned research icebreaker *Polarstern* as a central node in an observing network that will drift across the Arctic Ocean in 2019-20. Interdisciplinary science teams will work collaboratively to examine oceanic, atmospheric and sea-ice processes over the course of an annual cycle in the Arctic Ocean. Another example is the Greenland Ice Sheet Monitoring Network (GLISN), which is 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 calving. It also allows imaging the static and time-varying properties of the ice-sheet-bedrock interface and the underlying crust and lithosphere, which help control and respond to ice-sheet dynamics. Network data contribute to an improved understanding of landslides,

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tsunamis, and earthquakes, and to monitoring of earthquakes and explosions in the pan-Arctic region.

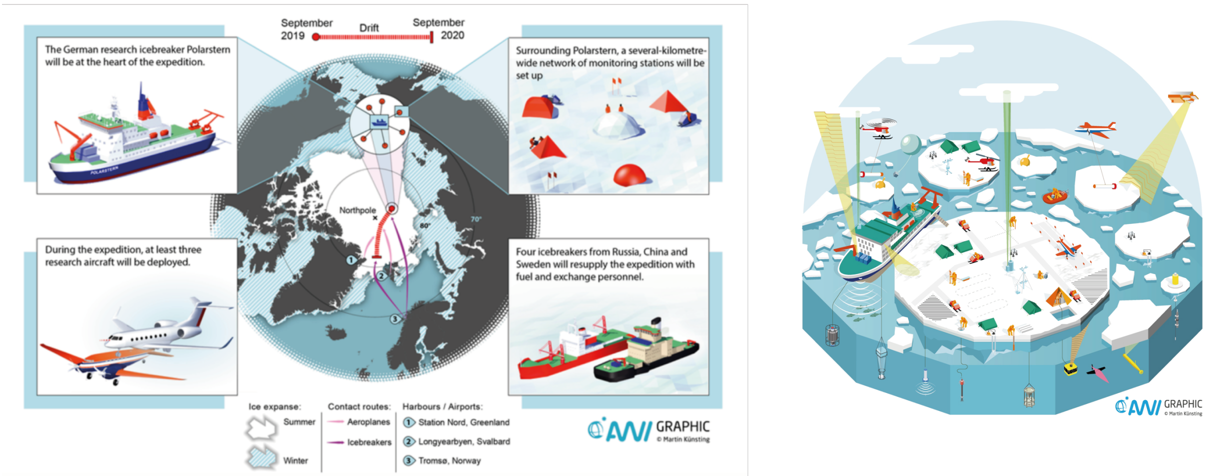

Diagram Credit: Alfred Wegener Institute

In Antarctica, NSF and the United Kingdom's Natural Environment Research Council (NERC) facilitated 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 will work together to understand the dynamics of Thwaites Glacier, which is thought to be a critical to the stability of the West Antarctic Ice Sheet. This study will further our understanding of ice-sheet dynamics and their implications for future sea-level rise.

The 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. The observational program at the South Pole is focused on two major goals: precision measurements of the Cosmic Microwave Background (CMB) and measurements of high energy neutrinos. The CMB is the oldest light in the universe and detected using a suite world-leading precision telescopes that shed light on the physics that governed the first moments after the Big Bang, and the structure and make-up of the universe. The IceCube Neutrino Observatory uses high energy neutrinos to probe the physics that generates the most energetic particles in the universe. This observatory consists of more than 5000 optical detectors deployed a mile below the surface of the ice sheet at the South Pole, Recently, IceCube made the first-ever detection of high energy neutrinos and provided compelling evidence of the first known source of cosmic rays. NASA's Long Duration Balloon program is also a unique platform for astrophysics and cosmology measurements in a near-space environment, and coordination between OPP and NASA is required to support this effort.

Continued participation in such large-scale, international science efforts supports NSF's Strategic Goals to expand knowledge through investing in ideas, people and infrastructure[13]. It also supports OPP mission to promote scientific discovery and understanding of the polar systems.

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Photo Credit: Dr. Daniel Michalik

Conclusion

OPP's historical investments in ideas, people and infrastructure have established fundamental knowledge about the Antarctic and Arctic. This foundation has yielded a much deeper appreciation of the importance of the connections between the polar regions and the global environment and society. However, polar regions remain ripe for fundamental exploratory research as well as research driven by significant changes that are underway. Answering these questions is critically important to the nation's economy, security and well-being as they present both threats and opportunities for society. OPP's continued investments in the human and physical capital needed for polar research will in addition lead to technological innovation applicable elsewhere, promote the development of the nation's workforce and enhance the capacity of its citizenry to understand be inspired by nature's processes and their influence on society.

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APPENDIX I

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 the Antarctica through Increased Logistical Effectiveness*.
   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 will drive NSF's long-term research agendas and push the frontiers of research across the agency.

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

6. 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.

7. U.S. Presidential Mandate 6646 (1982) https://www.nsf.gov/geo/opp/ant/memo_6646.jsp
   This Mandate 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.

8. 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.

9. Antarctic Treaty System https://www.ats.aq/e/ats.htm

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This website hosts documentation, including the Antarctic Treaty, related to the Antarctic Treaty System.

10. Arctic Council (2018) *Agreement 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."

11. 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 science priorities that will occur as the action items from the 2012 Blue Ribbon Panel report, *More and Better Science in the Antarctica through Increased Logistical Effectiveness,* are addressed. 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.

12. 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.

13. 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

14. 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:
    1. Role of the Arctic in the global system
    2. Predication of the future climate dynamics and ecosystem responses
    3. Improved understanding of the vulnerability and resilience of Arctic environments and societies.

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15. Office of Science and Technology Policy (2016) *Arctic Research Plan FY2017-2021.* *https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/iarpc_arctic_research_plan.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

16. Arctic Horizons Final Report. Retrieved from: http://arctichorizons.org/final-report#overlay-context=final-report

The input from Arctic research community, Indigenous communities, and stakeholder groups is synthesized into nine research priorities, 11 recommendations to facilitate the research and additional findings from the multi- and transdisciplinary workshops hosted throughout the Arctic Horizons project.

17. 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.

18. 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.

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19. 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.

20. Polar Geospatial Center (2013) *Report on Workshop on Cyberinfrastructure for Polar Sciences*. https://www.pgc.umn.edu/files/2018/05/2013-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.

21. 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.

22. Society for Industrial and Applied Mathematics (SIAM) (2018) *Research and Education in Computational Science and Engineering*. 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.

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

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