Working Document of the NPC Study:
Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources
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Paper #5-3

SUMMARY OF CURRENT ICE CHARACTERIZATION RESEARCH: U.S.

Prepared for the
Technology & Operations Subgroup

On March 27, 2015, the National Petroleum Council (NPC) in approving its report, *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Technology & Operations Subgroup. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 46 such working documents used in the study analyses. Appendix D of the final NPC report provides a complete list of the 46 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper

(Prepared for the National Petroleum Council Study on Research to Facilitate Prudent Arctic Development)

5-3	**Summary of Current Ice Characterization Research: U.S.**
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SUMMARY

This topic paper presents a summary of ice research programs currently performed in the United States in support of the NPC Arctic development study. In an attempt to focus this paper on research relevant to this study, it will not be an encyclopedic reference of every organization and every current research/measurement program with an Arctic ice theme. Another important note is that many high level organizations concerned with Arctic research will not be profiled in this paper in an effort to keep the scope focused on active research programs.

INTRODUCTION

Current ice studies in US Arctic waters are conducted by a broad range of organizations from Federal agencies to Oil and Gas companies. The purpose, scope, and scales generally differ considerably, with programs focused on a single aspect of ice to complex, multivariate process studies. While research on sea ice has seen steady efforts throughout much of the 20th century, with large-scale interdisciplinary studies such as AIDJEX (1970s), MIZEX (1980s), and SHEBA (1990s), there was a downtick in Arctic sea ice research activity in the early part of the first decade of the 2000s due in part to the discontinuance of the Office of Naval Research's Arctic Program. Ice research programs have seen renewed activity over the last 10 years due primarily for understanding an Arctic system under change and increased commercial activity.

There are many drivers that motivate researchers and organizations to study ice. Clearly climate change is a central theme, with studies documenting the evolving characteristics and behavior of ice. Characteristics are intended to include specific physical parameters, frequencies, and statistical distributions related to the ice itself, such as extent, concentration, composition, thickness, keel depth, mass, temperature profile, strength, and age, while behaviors tend to be seasonality, growth cycle, rheology, drift, stress, and deformation. Together with ancillary factors such as snow accumulation, melt ponds, albedo, lead/polynya formation are sought to improve numerical ice modeling and weather modeling. Growing accessibility within the Arctic has promoted increased activities and concerns in the following research driver categories; navigation, commercial shipping, tourism, resource extraction, economic opportunity, public safety, national security, coastal erosion, food security, subsistence use, critical habitats, and impact assessments.

In the study of ice, one cannot ignore the influence of the Metocean (oceanographic and atmospheric) conditions. These systems are intractably linked and a solid understanding of the ice is not possible without sufficient knowledge of its environment. The ice responds to the Metocean parameters. It drifts or deforms under influence of winds, it grows and ablates in response to heat fluxes and availability of solar radiation. At the same time, the ice plays a role in global weather systems and the oceanic thermohaline circulation.

Modeling is concerned with proper definition of initial conditions and understanding the essential variables of couplings, forcings, and feedbacks. Regardless of the model basis, the question is always: is the modeling getting it right for the right reasons? Coupling is evident as a change in one system imparts a change in the other. Forcings are one-way inputs such as wind on ice or atmospheric aerosols, while feedbacks signify a response interaction to a particular stimulus. Research and measurement programs help to inform the models with the ultimate goal of improving model skill.

Organizations conducting research or measurement programs are varied, however the majority are US Federal entities within the Departments of Interior, Commerce, and Defense and the National Science Foundation or academic programs that derive much of their funding from Federal sources. Rounding out the participants in US ice research is the private sector, which is lead by the oil and gas industry. For the purpose of this paper, it was desired to organize the discussions around the three player categories, however, distinguishing who does what and understanding the flow of funding within the Federal and Academic organizations can be complicated and lead to bit of redundancy. For instance, the Department of Defense is a top level funder of Arctic research in the US and has a published Arctic Strategy (November 2013) which outlines the Agency's aspirations in meeting The President's National Strategy for the Arctic Region[1] (April 2013). These aspirations are taken as directives by subordinate organizations within the DOD (e.g. US Department of the Navy), who in turn develop action plans and roadmaps

[1] http://www.whitehouse.gov/sites/default/files/docs/nat_arctic_strategy.pdf

that get executed by lower level organizations (ONR – NRL) or contracted externally as a grant.

During the research and preparation of this document, it became clear that there are a good number of organizations conducting Arctic ice research or measurement programs and each has its particular charge or purpose. Frequently, this results in programs that differ considerably in magnitude or focus of scope, however there is a trend for close relationships amongst many of the entities beyond their normal organizational boundaries. Collaboration and partnerships have been strongly embraced, further blurring the lines between who's doing what. There are a few organizations that are recognized for a particular aspect of ice research, such as the IABP and their Lagrangian ice drifter program, however IABP is comprised of 32 different organizations, many of whom appear in the following sections. The good news is that Arctic research can be held out as a positive example of cooperation of organizations that cover a broad spectrum of purpose and motivation. The cooperation comes as a solution out of need and not necessarily as a mandate, since it's an excellent way to stretch scarce research dollars and leverage capabilities of peer organizations.

The purpose of this Topic Paper is to present a summary of ice research programs currently performed in the United States in support of an overarching technical paper on Characterizing and Measuring the Ice Environment, which in turn advises a chapter on Arctic Research and Technology in the general National Petroleum Council research study. This study was requested by the Department of Energy as a basis for focusing '… on higher priority emerging research opportunities, technology development and collaborative approaches with applicability to continued prudent development of Arctic oil and natural gas resources.' Presumably, this study will help the DOE direct their resources and advise their Federal partners toward research and technology priorities that make sense at a Federal level. In an attempt to focus this paper on research relevant to address the charge from the DOE, this will not be an encyclopedic reference of every organization and every current research/measurement program with an Arctic ice theme. There will be deserving organizations or programs that go unmentioned in this paper and it should not be interpreted as a snub or oversight. Another important note is that many high level organizations concerned with Arctic research will not be profiled in this paper in an effort to keep the scope focused on active research programs. These organizations, such as the Interagency Arctic Research Policy Committee (IARPC) and United States Arctic Research Commission (USARC), play a critical role in Arctic research policy and promoting awareness; however they are detached from the act of conducting research.

It is important to recognize that ice research programs as addressed in this paper take on many different forms. They range from perpetual programs such as satellite based observations, characterization and statistical products from the NSIDC, and numerical modeling to one-off studies and expeditions.

FEDERALLY DRIVEN PROGRAMS

This section attempts to capture current research programs that are driven by, and for the most part executed through, a Federal entity or contractor. As mentioned in the Introduction, it can be a little challenging to map who does what, since one source may fund multiple parties and one program may have participation by multiple investigative organizations.

Bureau of Ocean Energy Management (BOEM)

The Environmental Studies Program (ESP) of the Bureau of Ocean Energy Management was established and funded by the United States Congress to support the offshore oil and gas leasing program of the U.S. Department of the Interior (USDOI) in pursuit of national energy policies. The consistent mandate of the ESP since its inception has been to establish the scientific information needed for assessment and management of potential impacts from oil and gas development on the human, marine and coastal environments of the Outer Continental Shelf (OCS).

The ESP operates on a national scale to assist in predicting, projecting, assessing and managing potential effects on the human, marine and coastal environments of the OCS that may be affected by oil and gas development. Lease-management decisions are enhanced when current, pertinent and timely environmental information is available. The ESP manages ongoing study projects in Alaska (currently about 50) in disciplines such as physical oceanography, air quality, fate and effects of pollutants, protected and endangered species, marine ecology, and the social sciences, including traditional knowledge. Early in the development of the program, the focus was on obtaining baseline information on the vast biological resources and physical characteristics of the Alaskan environment for pre-lease decision-making. These studies included biological surveys of marine species, basic oceanography and meteorology, and geologic and sea ice phenomena. As a broader base of information was established, it became possible to focus on more topical studies in smaller areas to answer specific questions and fill identified information needs.

Currently, a major portion of the ESP in Alaska is conducted on a collaborative basis with an extensive range of bilateral and multilateral partnerships. The ESP in Alaska coordinates routinely on major projects with numerous Federal entities, including: National Oceanographic Partnership Program (NOPP); National Oceanic and Atmospheric Administration (NOAA) and the National Marine Fisheries Service (NMFS) Alaska Fisheries Science Center; NOAA's National Marine Mammal Laboratory (NMML); U.S. Geological Survey (USGS)-Alaska Science Center; U.S. Fish and Wildlife Service (USFWS) and the Arctic Landscape Conservation Cooperative (LCC); USDOI Coastal Impact Assistance Program (CIAP); the North Slope Science Initiative (NSSI); National Aeronautics and Space Administration (NASA); National Science Foundation (NSF); U.S. Arctic Research Commission; and the Polar Research Board.

In addition, the ESP works directly on specific projects with the Alaska Ocean Observing System (AOOS); the North Pacific Research Board (NPRB); Alaska Department of Fish and Game (ADF&G); the North Slope Borough (NSB) Department of Wildlife Management; the Alaska Eskimo Whaling Commission (AEWC); and academic institutions including the University of Alaska Anchorage (UAA), University of Alaska Fairbanks (UAF), Woods Hole Oceanographic Institution (WHOI), University of Washington (UW), Idaho State University, and University of Texas (UT). The ESP also coordinates closely with active industry research and monitoring programs in Alaska conducted by BP, Shell Offshore Inc., ConocoPhillips, and others.

Current Studies

Enhanced Verification and Interpretation of Freeze-up Conditions for the Northeast Chukchi Shelf: Field Observations and Process Studies; Freeze-up Forecasts; and BOEM Sea Ice Database Enhancements - BOEM analysts and managers within the Alaska OCS Region seek more detailed spatio-temporal information pertaining to seasonal freeze-up conditions at specific planned drilling locations on the Alaska OCS. More reliable and extensive information is particularly needed during the late open-water season when storm activity is anticipated, and during the seasonal freeze-up period when frazil ice formation and pack ice intrusions create environmental concern for safe operations. Additional information pertinent to understanding the physics of freeze-up and associated forces that greatly impact Arctic offshore operations is also needed. Study products will be used for NEPA analyses, including Environmental Impacts Statements (EIS) and Environmental Assessments (EA), and related decision-making.

Crude Oil Infiltration and Movement in First-year Sea Ice: Impacts on Ice-associated Biota and Physical Constraints -This project will address some of the questions related to infiltration of oil into sea ice and its biological impacts. This is much needed information with regard to the analysis of any potential oil spills in the Arctic, particularly during winter months when ice cover is unavoidable. BOEM analysts and decision makers will use this information in NEPA analysis and documentation for Lease Sales, EPs and DPPs.

Development and Testing of a Low-Cost Satellite-Tracked Ice Drifter for Arctic Waters - The products will respond to BOEM's and the State of Alaska's needs to better understand ocean currents within the water column underlying sea ice and to better predict oil and contaminant trajectories in the nearshore in the event of a spill during the winter months. These low-cost ice drifters will be able to be easily deployed in ice-infested waters. The results from the ice drift study will provide new information on the stability of landfast ice, including in those areas that are heavily used by subsistence hunters. The capability to monitor large fragments of detached coastal sea ice in real-time would allow local communities, the State of Alaska, and Federal Agencies to track the movement of large ridges of ice that have the potential to be offshore marine mammal habitat or potential maritime hazards to shipping operations or subsistence hunting.

Characterization of the Circulation on the Continental Shelf Areas of the Northeast Chukchi and Western Beaufort Seas - The BOEM needs information on several aspects of the temporal and spatial structure of ocean currents in the northeastern Chukchi and western Beaufort seas. This characterization encompasses a description of the mean circulation under different wind and sea ice coverage conditions. This knowledge will be valuable for (a) improving the quality of information used in the Oil-Spill-Risk Analysis conducted by BOEM, (b) inferring the transport of zooplankton, contaminants and other quantities in key areas, (c) providing insight into the flow-related feeding aggregations of bowhead whales near Barrow, (d) providing important information for the preparation of NEPA documents, (e) providing information for ocean modeling efforts (including validation and skill assessment), and (f) complementing ongoing social research on offshore subsistence hunting. BOEM established the first operational use of High Frequency Radars (HFR's) to measure surface currents for the Beaufort and Chukchi seas. BOEM deployed HFR's in the central Beaufort Sea in 2005 and 2006. Beginning in 2009, BOEM supported the deployment of long range HFR's along the Chukchi Sea coast at sites located at Pt. Barrow, Wainwright and Point lay. In 2012, BOEM deployed the first use of extended range HFR's along the Chukchi coast. In 2013 through the help of funds from the Coastal Impact Assistance program (CIAP), a forth site was added at Cape Simpson along the western Beaufort coast to capture hourly surface currents from the western Beaufort Sea to the Chukchi Sea as far south as Point Lay. BOEM has integrated the use of extensive glider and shipboard surveys, moorings, drifters and other instrumentation to better understand the ocean circulation with the northeast Chukchi an Western Beaufort Seas. BOEM project web site… http://dm.sfos.uaf.edu/chukchi-beaufort/index.php.

MMS/BOEM has also funded extensive research on improving our understanding of landfast ice and s for the Chukchi and Beaufort Seas with the publication of two reports MMS 2005-068 and BOEM 2012-067 " Mapping and Characterization of Recurring Spring Leads and Landfast Ice in the Beaufort and Chukchi Seas" In addition, MMS/BOEM funded an extensive effort to understand strudel scour occurrence along the Beaufort Sea coast with the publication of MMS study 2009-017 "Mapping Sea Ice Overflood Using Remote Sensing: Smith Bay to Camden Bay"

Additional information: http://www.boem.gov/Environmental-Stewardship/Environmental-Studies/Alaska-Region/Alaska-Studies/index.aspx

Bureau of Safety and Environmental Enforcement (BSEE)

The Bureau of Safety and Environmental Enforcement (BSEE) works to promote safety, protect the environment, and conserve resources offshore through vigorous regulatory oversight and enforcement. The bureau develops standards and regulations to enhance operational safety and environmental protection in connection with the exploration and development of offshore oil and natural gas on the U.S. Outer Continental Shelf (OCS). The responsibilities of the bureau include permitting, inspections, offshore regulatory

programs, oil spill response, and newly formed training and environmental compliance functions. BSEE's Technology Assessment & Research (TA&R) program supports research regarding operational safety and pollution prevention related to offshore oil and natural gas and renewable energy exploration and development, and is an important part of BSEE's safety program.

Sea ice is the most severe environmental factor in the Arctic. The hazards it creates are potentially greater than the hazards faced in open-ocean operations. Such hazards range from the forces that moving sea ice exerts against offshore structures to the gouging of the seafloor (a factor to be considered in the placement of pipelines). Engineering data for these hazards is important as operations move from exploration to production and as structures are considered for deeper water. BSEE actively participates in opportunities to gain safety-related information in advance of future operations in the Arctic.

Current Studies

2013-14 Freeze-Up Study - The 2013-14 Freeze-Up Study is intended to build upon the knowledge and expand the database acquired during the past four years and is designed to address five specific objectives:

- Describe the ice conditions that evolve during the freeze-up and early winter seasons, including the development of the landfast ice zone and early shear zone;
- Locate and map features of potential importance for offshore exploration and production activities, including ice movement lines, substantial leads (linear openings in the sea ice) and polynyas (areal openings in the sea ice), first-year ridges and rubble fields, and multi-year floes;
- Locate and map ice pile-ups on natural shorelines and man-made structures, and estimate the dimensions associated with such features;
- Correlate significant changes in the ice canopy with the corresponding meteorological conditions;
- Using the data acquired since 2009-10, characterize present-day freeze-up processes and compare them with those documented in the 1980s.

Grounded Ice Feature in the Beaufort Sea - "In February 2012, a large, grounded ice feature was discovered off the Chukchi Sea coast in the vicinity of Point Belcher. Based on the likelihood that a substantial ice gouge had been incised in the sea bottom, a joint industry project was commissioned to perform a bathymetric survey at the site immediately after break-up of the sea ice. The work was sponsored by Shell International Exploration and Production, Inc., Statoil Petroleum AG, and the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE).
The primary objective of the project was to document the gouge created by the grounded ice feature. Secondary objectives were to investigate the nature of the feature itself, and to investigate the characteristics of the sea bottom sediment."

Reliability-Based Sea-Ice Parameters for Design of Offshore Structures - "The objective of this project is to produce information that will facilitate strict implementation

of the ISO 19906 Standard: Petroleum and Natural Gas Industries - Arctic Offshore Structures (i.e., the Normative). The information will consist of sea-ice information, for U.S. waters in both the Chukchi and Beaufort seas, in a format consistent with the philosophy of the Normative.

Currently, implementation of ISO 19906 in U.S. waters is questionable due the lack of sea-ice design criteria. Appendices B.7 (Beaufort Sea) and B.8 (Chukchi Sea) of ISO 19906 are intended to provide this information, but numerical values are sparse and the format of the data is not consistent with the philosophy of the Normative – i.e., a reliability-based format. A full complement of design values for the regions covered in B.7 and B.8 is required to implement the normative provisions and, ultimately, produce safe and reliable offshore structure designs."

The Effects of Healing on the Resistance to Frictional Sliding of Sea Ice - The overall objective of the proposed research is to describe a systematic series of slide-hold-slide (or start-stop-start) experiments on first-year sea ice, designed to determine the effect of healing on the resistance to frictional sliding of ice-on-ice. Frictional sliding plays a fundamental role in the brittle compressive failure of sea ice and, in ice loading of structures. The effort will be performed in Dartmouth's Ice Research Laboratory, and will utilize a recent upgrade of those facilities, with the objective of improving the ability to predict ice-induced loads on engineered structures used in the exploration and production of oil and gas from beneath the ice cover on the Arctic Ocean.

Additional information: http://www.bsee.gov/Research-and-Training/Technology-Assessment-and-Research/tarprojectcategories/Arctic-Research-Projects/

National Science Foundation (NSF)

The Division of Polar Programs (POLAR) manages and initiates National Science Foundation funding for basic research and its operational support in the Arctic and the Antarctic. The funds are provided as NSF grants to institutions (mainly U.S. universities), whose scientists perform the research at the institutions or in a polar region, and as cooperative agreements or contracts to support organizations including contractors and the U.S. military[2].

POLAR supports individual investigators or research teams and U.S. participation in multinational projects. Projects can involve investigators from many disciplines and institutions over several years.

Organizationally, POLAR has two science sections- one for the Arctic and the Antarctic. A third section manages the logistics and support operations including field stations, camps, laboratories, ships, and airplanes. Environmental, health and safety issues are handled by the Polar Environment, Health and Safety Section.

[2] https://www.nsf.gov/geo/plr/about.jsp

The United States is a leading nation in polar science, and research results have global significance. Because the polar regions intrigue the public, they provide opportunities for educational enrichment.
Polar regions are unique natural laboratories. A range of research can be undertaken only there or best there. POLAR considers supporting polar research in these areas:

- **Understanding Earth and its systems.** Goals include achieving better understanding of polar regions' influence on and response to global heat distribution in the oceans and the atmosphere, adaptations of organisms to polar extremes, and the valuable records of past climates and atmospheric constituents in ice cores, polar ocean sediments, and other indicators.
- **Exploring the geographical frontier.** Many fields of science are exploring the still unevenly understood polar frontiers. For example, the central Arctic Ocean and the Southern Ocean are the least studied oceans, especially during winter.
- **Performing science enabled by the polar setting.** Polar conditions can enable research either not possible elsewhere or less effective elsewhere. Examples are the extremely dry atmosphere over the South Pole as a window for astrophysical study of the origins of the universe, arctic social sciences, and antarctic medical sciences.

United States Coast Guard (USCG)
Science operations, research, and development in the Arctic have long been significant U.S. Coast Guard mission sets. Modern research projects help the service to meet hazards and threats in this remote locale. In support of these missions, the U.S. Coast Guard created the Research and Development Center (RDC), a facility that provides research and development, as well as testing and evaluation services. These efforts are broad and varied, support the acquisitions and regulatory processes, and improve overall Coast Guard operations and mission support.[3]

Continuing Arctic challenges include safe natural resource development, protecting wildlife and fish stocks, supporting safe shipping tourism, and ensuring food security for the indigenous communities. We
are witnessing environmental and ecosystem changes in this region, demonstrating its fragile nature.
Support for Arctic science has been an important part of Coast Guard missions, and the demand for polar science and technology has never been greater. Whether it is oil spill response capability, improved response assets, or new anti-icing technology, the RDC is helping the Coast Guard chart an appropriate
course for its expanding Arctic operations. It is clear that the Coast Guard has an enduring role in protecting the maritime Arctic by providing safety, security, and stewardship, while supporting our nation’s science needs.

[3] http://www.uscg.mil/acquisition/pdf/Vol70_No2_Sum2013_page77.pdf

Evaluating Arctic Capacity - The center's efforts in the Arctic region include delivering a high latitude study in July 2010, which evaluated polar icebreaker capabilities, requirements, and Arctic and Antarctic mission needs. To address the aging polar-class icebreakers, RDC also conducted a business case analysis that explored several options from major overhauls to icebreakers Polar Sea and Polar Star, as well as new build and lease options. The Department of Homeland Security forwarded this report to Congress in November 2011.

Search and Rescue Challenges - At this time, the Coast Guard has no data on appropriate search swipe widths to assist search and rescue (SAR) mission controllers in developing search plans for ice-covered waters. Should a maritime mishap occur in the icy Arctic waters, search and rescue controllers
have only "liquid-water" search performance data available to guide search pattern assignments for
response craft. The RDC is addressing this SAR planning data gap by conducting mission-realistic search performance tests in the Great Lakes during winter weather conditions to develop a preliminary set of search planning data for Coast Guard helicopters and airboats searching ice-covered waters.

Response Asset Assessment - The Research and Development Center continues to address Arctic capability gaps by investigating response craft and cutter boats capable of operating in the Chukchi and Beaufort Seas. The results document a search of all types of craft for potential use in the Arctic. Based on these findings, the Coast Guard invited industry to propose solutions that would then
be brought up to the waters off Barrow, Alaska, to demonstrate their ability to meet the Coast Guard's
needs. Two craft, selected from a field of industry proposals were tested, and the RDC delivered a report on the results in 2012.

Department of Defense (DOD)

The DoD Arctic Strategy[4] outlines how the Department will support the whole-of-government effort to promote security, stewardship, and international cooperation in the Arctic. The Department's strategic approach to the Arctic reflects the relatively low level of military threat in a region bounded by nation States that have not only publicly committed to working within a common framework of international law and diplomatic engagement, but have also demonstrated the ability and commitment to do so. In consideration of enduring national interests in the Arctic and existing strategic guidance, the Department's end-state for its strategic approach to the Arctic is: a secure and stable region where U.S. national interests are safeguarded, the U.S. homeland is protected, and nations work cooperatively to address challenges.

[4] http://www.defense.gov/pubs/2013_Arctic_Strategy.pdf

The Department will pursue comprehensive engagement with allies and partners to protect the homeland
and support civil authorities in preparing for increased human activity in the Arctic. Strategic partnerships
are the center of gravity in ensuring a peaceful opening of the Arctic and achieving the Department's desired end-state. Where possible, DoD will seek innovative, low-cost, small-footprint approaches to achieve these objectives (e.g., by participating in multilateral exercises like the Search and Rescue Exercise (SAREX) hosted by Greenland, COLD RESPONSE hosted by Norway, and Canada's Operation NANOOK, or through Defense Environmental International Cooperation Program-supported engagements on Arctic issues). The Department will also evolve its infrastructure and capabilities in step with the changing physical environment in order to ensure security, support safety, promote defense cooperation, and prepare to respond to a wide range of challenges and contingencies in the Arctic in the coming decades.

The Department will accomplish its objectives through the following ways.

- Exercise sovereignty and protect the homeland;
- Engage public and private sector partners to improve domain awareness in the Arctic;
- Preserve freedom of the seas in the Arctic;
- Evolve Arctic infrastructure and capabilities consistent with changing conditions;
- Support existing agreements with allies and partners while pursuing new ones to build confidence with key regional partners;
- Provide support to civil authorities, as directed;
- Partner with other departments and agencies and nations to support human and environmental safety; and
- Support the development of the Arctic Council and other international institutions that promote regional cooperation and the rule of law.

The Department of Defense coordinates research initiatives with the Interagency Arctic Research Policy Committee (IARPC) and works with other Federal Departments and agencies to[5]:

- Improve nautical charts
- Enhance relevant atmospheric and oceanic models
- Improve accuracy of estimates of ice extent and thickness
- Detect and monitor climate change indicators
- Improve hydrographic charting and oceanographic surveys
- Work with the State of Alaska to monitor and assess changes in the physical environment to inform the development of Arctic requirements and capabilities
- Leverage work done by the scientific and academic communities and seek opportunities to contribute to the observation and modeling of the atmosphere,

[5] http://www.acq.osd.mil/chieftechnologist/publications/docs/IARPC_Brief_FINALNOBACKUP.pdf

ocean, and ice conditions, to enhance military environment forecasting capabilities

DoD, as a high-level funder and Arctic policy originator, points mostly to ONR and DARPA for examples of their current research initiatives. However, the DoD is directly involved in the development of the Arctic Collaborative Environment (ACE), which is described as: A Web-based, open-source military, civilian whole of government Arctic Collaborative Environment and Decision Support System that leverages NASA, other government agencies investments in Arctic research to integrate disparate data, existing and new environmental models, and in-situ reporting to provide monitoring, analysis, and visualization products layered within user-configurable map displays and integrated into a community-based collaborative environment. Includes arctic sea ice flow and characteristics, sea surface temperatures, state, and currents from U.S. agencies and partner nations.

Department of Energy (DOE)

DOE's Office of Science, Climate and Environmental Sciences Division seeks to understand the impacts of energy production and use on the climate and environment and to provide the tools needed to evaluate potential futures and the impacts on future energy systems. To that end, DOE sponsors an integrated portfolio of process and modeling science aimed at developing predictive, systems-level understanding of the fundamental science associated with climate change. The following are high priority Arctic research topics for DOE's Office of Science. DOE is focused on these issues because they have important regional and global implications (and thus are important to entities other than just DOE). Additionally, each of these areas has, or is likely to garner, interagency collaboration.

Terrestrial Ecology - Improved understanding of Arctic permafrost carbon in a changing climate – and capture of that understanding in large-scale models - There is much more carbon frozen in Arctic permafrost than there is in the atmosphere. Permafrost thaw is being documented across the Arctic and is projected to expand in future years. As the carbon frozen in permafrost thaws, it will decay. The rate and nature of that decay will determine the rate of release of CO2 and methane from permafrost to the atmosphere with associated changes in land surface, hydrology, vegetation, and other key variables.

Next Generation Ecosystem Experiment - Arctic: NGEE-Arctic is designed to deliver a process-rich ecosystem model, extending from bedrock to the top of the vegetative canopy, in which the evolution of Arctic ecosystems in a changing climate can be modeled at the scale of a high resolution Earth System Model grid cell (i.e., 30x30 km grid size). In a novel ecosystem approach, the NGEE project has closely linked the modeling and process components of this project. In this way, modelers are asked to grapple with the complexity of the natural system and ecologists are asked to appreciate the necessity of simplified representation of these systems in models. Models are developed with input from ecologists and field sampling is designed with input from the

modeling team. The goal is to short circuit the standard approach of advances in process understanding followed by translation into model representation.

Collaborative opportunities: There are multiple levels of opportunity for collaboration with NGEE-Arctic. Single investigator-scale collaboration is encouraged where NGEE provides a convenient platform, data/sample source for other investigators. Leveraging the infrastructure and physical resources made available by the NGEE project. Project-scale collaborations are being developed whereby research investments from other agencies are connected to and/or leveraged by NGEE-Arctic.

Atmospheric processes – Improved understanding of atmospheric processes in the Arctic – and capture of that understanding in regional and global models - The Arctic environment is changing rapidly. To understand the reasons for this, the Interagency Arctic Research Policy Committee (IARPC) identified a set of key atmospheric issues including the role of short-lived climate forcers (such as black carbon and methane) on Arctic warming; the complex processes that control the formation, longevity, and physical properties of Arctic clouds; and integrating Arctic atmospheric processes with the surface energy budget and the oceanic, terrestrial, and cryospheric systems.

- Arctic observations for atmospheric process studies: The Atmospheric Radiation Measurement program (ARM) has made important long-term measurements of aerosol, cloud, atmospheric, and surface properties at its North Slope of Alaska (NSA) Barrow site and has recently deployed the third ARM Mobile Facility (AMF) to a new measurement site at Oliktok Point, Alaska. ARM will link the near-coast facilities and the adjacent ocean together into an NSA "mega-site". As part of this NSA mega-site, ARM will deploy manned aircraft along with Unmanned Aerial Systems (UAS), including tethered sondes and small unmanned aircraft, to provide vertical and horizontal sampling of atmospheric and surface properties. The improved and higher density measurements made at the NSA mega-site will open new opportunities for Atmospheric System Research Program-supported process studies to further understanding of Arctic cloud, aerosol, radiation, and precipitation processes to improve the representation of these processes and their feedbacks on climate in global and regional models. ARM also supports requests for guest instrument deployments, manned/unmanned aircraft flights, and intensive observing periods at its Arctic facilities.

Enhance and test modeling capabilities to understand and project Arctic climate changes and feedbacks - Climate change at high latitudes is proceeding at a rate 2-3 times faster than the global mean, with significant reductions in Arctic sea-ice extent, acceleration of sea level rise due to ice sheet melt, modification of ocean circulation and biogeochemical exchange, and thawing of permafrost. These changes will have impacts not only on polar ecosystems and human activity in the polar-regions but also on global circulation and climate. It is imperative that individual climate system components and

the fully coupled system accurately simulate previous decades of changes in order to project future Arctic climate changes.

- DOE is investing in next-generation modeling capabilities, including that of the Community Earth System Model (CESM), the Accelerated Climate Model for Energy (ACME), and the Regional Arctic System Model (RASM), to improve the representation and predictive capability of Arctic sea-ice, land-ice, ocean, clouds, and terrestrial components in global and regional climate models. DOE has also developed a new variable-resolution modeling framework that permits focused resolution in selected areas of interest. Current projects are configuring climate models with enhanced spatial resolution in high-latitude regions to perform simulations that address outstanding problems in high-latitude climate change, including changes in Arctic sea-ice, Greenland ice sheet mass loss and consequent sea-level rise, changes in high-latitude clouds and atmospheric conditions, changes to ocean circulation, resulting impacts on polar ecosystems and carbon cycle, and feedbacks among these components. New analysis tools for understanding high-latitude processes and new metrics and testbeds to evaluate the performance of models in polar regions are being built and will be shared with the community.

National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration (NOAA) is actively engaged in the Arctic, providing science, service, and stewardship to this rapidly changing region, its inhabitants, and the Nation. Through its broad range of activities, NOAA is well prepared to make significant contributions, to the extent possible within existing resources, to all three lines of effort in the recently released U.S. National Strategy for the Arctic Region (May 2013) and its subsequent Implementation Plan (January 2014). As described in its 2011 Arctic Vision and Strategy, NOAA has six strategic goals in the Arctic, each of which directly supports the National Strategy[6].

- Forecast sea ice
- Improve weather and water forecasts and warnings
- Strengthen foundational science to understand and detect Arctic climate and ecosystem changes
- Improve stewardship and management of ocean and coastal resources in the Arctic
- Advance resilient and healthy Arctic communities and economies
- Enhance international and national partnerships

NOAA has many diverse and robust programs underway in the Arctic. NOAA's Arctic Action Plan describes those efforts, how they implement NOAA's Arctic Vision and Strategy, and how they support and harmonize with the National Strategy for the Arctic

[6] http://www.arctic.noaa.gov/NOAAarcticactionplan2014.pdf

Region. This document lays out concrete objectives to set priorities, leverage partnerships, and build upon accomplishments, to the extent possible within existing resources.

NOAA conducts sea ice research to better understand the drivers and associated impacts that cause ice to form and melt. Sea ice research is especially important due to the high impact of sea ice distribution on transportation, marine ecosystems, resource development, search and rescue operations, national security, and global climate. NOAA's research efforts are focused on improving sea ice predictions and models as well as understanding the consequences of increased sea-ice-free areas on Arctic ecosystems and mid-latitude weather.

Researchers are exploring the direct connection between melting Arctic sea ice and weather extremes in the mid-latitude United States, which has broad implications for NOAA's stewardship and environmental prediction missions.

NOAA is meeting the growing challenges of Arctic change and the impact of those changes in other regions by launching a five-year science initiative on predicting Arctic weather and climate connections with mid-latitude zones.

Future goals include leveraging and expanding observation, modeling, and forecast capacity, as well as improving models that couple atmosphere, ocean, land, and ice at local, regional, and global scales. Arctic services are best accomplished by sharing data at multiple levels – among universities and researchers, commercial ventures, other Arctic countries, and non-Arctic
countries possessing Arctic capabilities. NOAA intends to expand these relationships through partnerships and formal bilateral/multilateral arrangements, increasing both its interagency and international partnerships to improve the accuracy, timeliness, and coverage of forecasts.

NOAA offices with lead responsibility for Arctic milestones National goals supported by NOAA milestones:
NESDIS - National Environmental Satellite and Information Service
NMFS - National Marine Fisheries Service
NOS - National Ocean Service
NWS - National Weather Service
OAR - Office of Oceanic and Atmospheric Research
OIA - Office of International Affairs
OMAO - Office of Marine and Aviation Operations

Current Research

Collect observations to enable modeling and analyses of Arctic sea ice to provide the necessary information and understanding required to support sea ice forecasts and advisories. [OAR – NOP]

Continue research to analyze and synthesize in situ, remote sensing, and model data for Arctic Ocean seasonal sea ice and the tropospheric impacts of loss of sea ice. [OAR – NOP]

Undertake research and model-based analyses that investigate the current status, future changes, and interactive processes related to sea ice drift, sea ice thickness, and snow cover on ice. [OAR – NOP]

Conduct coordinated calibration and validation of satellite measurements of the cryosphere through in-situ and airborne missions in collaboration with national and international partners. [NESDIS – NOP]

Issue routine sea ice analyses, forecasts, advisories, and outlooks 5-days per week in a variety of formats to be useful from the community level to the federal stakeholders and partners; continue to provide non-routine tactical support services as needed for core partners. [NWS – NOP]

Advance our sea ice services through the addition of more observational data sets to our analysis and forecasting techniques, evaluations of coupled model output from Environment Canada and the Naval
Research Laboratory, and the expansion of product suites with new and more frequent services. [NWS – NOP]

Produce and disseminate routine weather forecasts and non-routine alerts of hazardous conditions (high winds, winter storms, thunderstorms, wildfire conditions, floods) across Alaska 365 days a year. [NWS – NOP]

Address weaknesses in our communications infrastructure to ensure more reliability/redundancy in forecast and warning dissemination. [NWS – NOP]

Continue to modernize and make more efficient our observational networks through the installation of hydrogen generators; automated marine, aviation, and river observing platforms; and in leveraging partnerships for infrastructure and data sharing wherever possible. [NWS – NOP]

Establish foundational components of a Regional Operations Center and Arctic Test Bed to strengthen NOAA's ability to be responsive to emerging service requirements in the Arctic and leverage new science
and technology capabilities. [NWS]

Produce and disseminate routine aviation weather forecasts and nonroutine alerts of hazardous conditions (turbulence, icing, fog, wind shear, volcanic ash) for the airspace in and around Alaska 365 days a year. [NWS]

Produce and disseminate routine weather forecasts and warnings of hazardous conditions (high winds, waves, freezing spray, fog, thunderstorms) for the coastal and offshore waters around Alaska 365 days a
year. [NWS]

Develop an implementation plan for seamless marine weather services across the Arctic and in accordance with World Meteorological Organization standards. [NWS]

Lead the effort to validate the requirements for climate-scale Arctic specific forecasts for weather and sea ice to inform and prioritize NOAA's research and observing investments. [NWS – NOP]

Integrate new satellite-derived sea ice information into National Ice Center operations, such as ice thickness, ice concentration, and size of leads (fractures) in ice. [NESDIS – NOP]

Improve snow depth, snow cover, ice cover, and ice thickness analysis for operational model initialization or assimilation. [NESDIS – NOP]

Coordinate with national and international partners to broaden geographic coverage of Arctic sea ice analysis and forecasting by calibrating single-point buoy/mooring data with satellite data. [NESDIS – NOP]

Conduct sustained observations in key regions of the Chukchi Sea, Beaufort Sea, East Siberian Sea, and Pacific Arctic Ocean with interagency and international partners to support the Russian-American Long-term Census of the Arctic (RUSALCA) Program and other research initiatives. [OAR]

Maintain, strengthen, and enhance atmospheric climate observatories and monitoring sites around the Arctic Rim to capture measures of variability and change; continue to improve data management to support analyses to understand the causes and implications of those changes both in the Arctic and in the Northern Hemisphere. [OAR – NOP]

NOAA is a broad reaching organization in Arctic research and has considerable Arctic research in subordinate or dependent organizations, such as PMEL and NCEP.

Pacific Marine Environmental Laboratory (PMEL) - NOAA's Pacific Marine Environmental Laboratory (PMEL) is a federal laboratory that makes critical observations and conducts groundbreaking research to advance our knowledge of the global ocean and its interactions with the earth, atmosphere, ecosystems, and climate. PMEL's mission is to a) observe, analyze, and predict oceanic and atmospheric phenomena, b) lead the development and deployment of innovative technologies, c) identify and understand ocean-related issues of major consequence, and d) inform society with well-documented, high quality science. Key research areas at PMEL include ocean

acidification, tsunami detection and forecasting, hydrothermal vent systems, fisheries oceanography, and long term climate monitoring and analysis.[7]

- **Arctic Climate Dynamics -** The Arctic Climate Dynamics group conducts observations and evaluates models of Arctic sea ice to document and predict climate change impacts on Arctic marine ecosystems. The group is also documenting Bering Sea changes, where research suggests a shift from predominantly interannual variability to decadal variability.

  Climate change in the Arctic presents a need for expanded research in support of NOAA's climate program. The Arctic has evolved to a "new normal" that lies outside the bounds of recent natural variability. Opportunities for the Arctic Climate Dynamics group include: developing new capabilities for NOAA sea ice forecasting on weekly, seasonal, and decadal scales; providing baseline observations for the Beaufort and Chukchi seas; detecting and predicting changes in physical, chemical, and biological structure and dynamics in the U.S. Arctic marine environment; evaluating the potential for strengthened linkages between Arctic climate change and mid-latitude extreme weather events; and determining causes and estimating future impacts of changes in atmospheric composition and radiative fluxes.
- **Marginal Ice Zone Studies -** From October 21 to November 6, 2013, the PMEL Arctic team utilized the heavily-instrumented NOAA WP-3D Orion "Hurricane Hunter" research aircraft to complete the first intensive Arctic overflight experiments to make quantitative measurements of autumn sea ice freezeup in the Chukchi sea, a region of potential oil exploration. The objective of the flights was met by successfully making measurements of the ocean, and of the atmosphere over open water, first year ice, and multi-year ice, under a variety of weather conditions, during the freezeup.
- **Sea Ice Outlook -** Another activity relevant to sea ice includes participation in the SEARCH Sea Ice Outlook an international effort to provide a community-wide summary of the expected September arctic sea ice minimum. Monthly reports released throughout the summer synthesize community estimates of the current state and expected minimum of sea ice—at both a pan-arctic and regional scale. The intent of the SEARCH Sea Ice Outlook effort is not to issue predictions, but rather to summarize all available data and observations to provide the scientific community, stakeholders, and the public the best available information on the evolution of arctic sea ice. Sea Ice Outlook activities are supported by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and through the volunteer efforts of contributors. The Outlook is organized by the SEARCH Project Office at the Arctic Research Consortium of the U.S. (ARCUS). The pan-arctic monthly reports are synthesized by the Arctic Climate Dynamics group leader James Overland.

[7] http://www.pmel.noaa.gov/arctic/

- **Arctic Climate Change -** The Arctic Climate Dynamics group provides scientific support for decision makers on climate change and ecosystems in the Arctic and sub-Arctic, leading projects on: historical climate changes, climate and sea ice projections in northern latitudes mid-latitude linkages, ecosystem indices in the Bering Sea, and the Arctic Report Card and Sea Ice Outlook Websites.

  The group has contributed to the government response to the Endangered Species Act listings for polar bears, ribbon seals and spotted seals, to the NOAA Arctic Action Plan, and to the Arctic Transportation Study. The group supports the Arctic Council and the International Arctic Science Committee on Arctic Climate Change, and advises NOAA fisheries managers on climate change issues, which in turn helps set fisheries quotas for the Bering Sea.

Defense Advanced Research Projects Agency (DARPA)

To enable future capability for regional situational awareness and maritime security, DARPA's Assured Arctic Awareness (AAA) program plans to develop new technologies for an advanced distributed sensor system to monitor the Arctic both above and below the ice, providing year-round situational awareness without the need for forward-basing or human presence. The program seeks advances in sensor systems and related technologies—such as station-keeping capabilities—that are rugged enough to withstand Arctic conditions, economical to operate and environmentally responsible with minimal impact.

The program's goal is to identify compelling system concepts enabled by new technologies which enhance future maritime security in a cost-effective and responsible manner.

Assured Arctic Awareness – research should investigate innovative approaches that enable revolutionary advances in science, devices, or systems. Specifically excluded is research that primarily results in evolutionary improvements to the existing state of practice, that requires development of new manned or space-based platforms, or that is only a concept of employment or operations using existing platforms and systems.
The contractor will determine the changes in the Arctic acoustic environment due to the thinning and retreating ice over. The measurements will be performed by using one source array and one receive array deployed in the ice.
The contractor had developed the concept of an air-deployed Field-distributed, Low-cost, Open-water, and Acoustic, Thin-ice Sensor (FLOATS) system for passive acoustic under-ice awareness to exploit the new and unprecedented Thin-ice Arctic Acoustic Window (THAAW) conditions that exist today and will continue over the next two to three decades.

The Contractor proposes to further develop the FLOATS concept and, in doing so, conduct a data collection effort in the Arctic to quantify the hypothesized THAAW physics and provide data to validate the FLOATS system concept's performance metrics.

National Snow and Ice Data Center (NSIDC)
NSIDC scientists are known internationally for their expertise in a range of fields related to the cryosphere. In-house scientists investigate the dynamics of Antarctic ice shelves, monitor the links between Arctic sea ice and climate, study new techniques for the remote sensing of snow and freeze/thaw cycles of soil, account for snow in hydrologic modeling, research large-scale shifts in polar climate, investigate seasonally and permanently frozen ground, and work to improve understanding of river and lake ice. Browse the table below to view project summaries.

Scientists pursue their work as part of the CIRES Cryospheric and Polar Processes Division, at the University of Colorado at Boulder. National agencies fund research through the peer review proposal process.

Current Research

An Innovative Network to Improve Sea Ice Prediction in a Changing Arctic - Recent major changes in the extent, thickness and properties of Arctic sea ice have captured attention and posed significant challenges to a diverse group of stakeholders, ranging from maritime safety and security, resource management and development, politicians, coastal communities, weather and climate forecasters, climate change researchers, and a growing segment of the general public. Sea ice forecasting on interannual and seasonal time scales, especially over the summer and into fall, is of particular interest. Though each stakeholder is driven by different priorities, all require improved monitoring, prediction, and communication of sea ice conditions. To date, sea ice modeling efforts have largely focused on climate scales (i.e., response to greenhouse gas forcing) or targeted synoptic forecasting in support of navigation. Sea ice forecasting on seasonal scales is a challenge because of: (1) high variability in atmospheric and oceanic influence, (2) observations for initialization and validation have limited coverage and/or high uncertainties, (3) current model capabilities are limited, (4) inherent limitations in sea ice predictability, and (5) an Arctic system changing in ways without recent historical precedent.

The SEARCH Sea Ice Outlook was implemented four years ago in an ad hoc fashion, requesting voluntary contributions to estimate September sea ice extent based on late spring (June 1) conditions. Contributions have been made using different methods that vary from complex (partially- and fully-coupled general circulation models and statistical relationships) to basic (linear trend extrapolation, heuristic, public poll). We propose to organize and expand the Outlook into a more structured, coordinated and formal effort that focuses on tackling key barriers to sea ice forecasting, including rigorous evaluation of predictions, coordination and organization of relevant observations for initialization, evaluation of methods, and finally, an organizational network structure to manage the efforts and communicate results in new ways. This proposal builds on the experience of the past four years and expands on structures already in place, leveraging resources and expertise at an international scale to help address a set of challenges recognized as priorities by a range of U.S. and international programs and organizations.

Operation IceBridge - NSIDC manages data for products derived from NASA's Operation IceBridge aircraft missions, and implements tools and services extending the uses of IceBridge data products.

The Operation IceBridge mission, initiated in 2009, collects airborne remote sensing measurements to bridge the gap between NASA's Ice, Cloud and Land Elevation Satellite (ICESat) mission and the upcoming ICESat-2 mission.

IceBridge mission observations and measurements include coastal Greenland, coastal Antarctica, the Antarctic Peninsula, interior Antarctica, the southeast Alaskan glaciers, and Antarctic and Arctic sea ice.

The NASA IceBridge mission combines multiple instruments to map ice surface topography, bedrock topography beneath the ice sheets, grounding line position, ice and snow thickness, and sea ice distribution and freeboard. Data from laser altimeters and radar sounders are paired with gravitometer, magnetometer, mapping camera, and other data to provide dynamic, high-value, repeat measurements of rapidly-changing portions of land and sea ice.

The Dynamics of Human-Sea Ice Relationships: Comparing Changing Environments in Alaska, Nunavut, and Greenland - This project is also referred to as "Siku-Inuit-Hila" (Sea ice, people, and weather). The research team includes social and physical scientists and members of each community: Barrow (Alaska), Clyde River (Nunavut) and Qaanaaq (Greenland). The project relies heavily on fieldwork conducted by the whole team in each community. Comparisons of sea ice use and changes are the focus of workshops and field excursions. The team will also establish ice monitoring stations, which are monitored by local observers to record the ice growth and melt cycle at key locations for each community.

In recent years, Arctic sea ice has been thinning, retreating, and changing its patterns of freeze up and break up. For many indigenous communities in the Arctic, sea ice use and human-sea ice relationships that are deeply rooted in time, as well as identity, are being challenged. There is an urgent need for scientists, decision makers, and others to better understand the human and social dynamics surrounding Arctic sea ice change, what is at stake for coastal communities, and what the responses might be. Using the unique approach of an international, multidisciplinary, and multicultural "sea ice knowledge exchange," the investigators, in partnership with indigenous sea ice experts (hunters and Elders) from three regions of the Arctic (Barrow, Alaska; Clyde River, Nunavut, Canada; and Qaanaaq, Greenland), will conduct a comparative study across these three communities.

Evaluation of Arctic and Antarctic Sea Ice - Stroeve et al. [2007] previously investigated sea ice model output from models participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The study noted that

while all models realistically capture the climatological mean and seasonal cycle of Arctic sea ice as shown in a previous study [Zhang and Walsh, 2006], none of the models or individual model simulations show trends as large as observed over the period of reliable observations (1953-present). Even accounting for annual-to-decadal variability in both observed and modeled trends, the AR4 models as a group were found to be too conservative regarding the loss rate, and the date at which a seasonally ice free Arctic Ocean may be realized. This has become even more apparent after the last four years of continued record low ice extents.

We plan to repeat the study of Stroeve et al. [2007] using the latest model data for the IPCC Fifth Assessment Report (AR5). Besides investigating trends in the modeled sea ice extent and how these compare with those in the observational record, we will also evaluate sea ice mass budgets for the 20th century and projected changes through the 21st century. Comparisons with limited amount of observational ice thickness data will be made, and models that incorporate ice age tracers will be compared with the Maslanik et al. [2007] ice age product. Differences in modeled values of the ice extent and mass budgets will be then evaluated in terms of their thermodynamic and dynamic contributions.

Cryospheric Applications of Landsat 8 - Landsat 8 was launched on 11 February 2013, and has begun to acquire excellent images of the globe, including both polar ice sheets, mountain glaciers and sea ice. The quality of the Landsat 8 sensor supports several applications for mapping of snow and ice surfaces. This contract supports work on development of algorithms using Landsat 8 visible and thermal data for snow, ice, and sea ice research.

Cold Regions Research and Engineering Laboratory (CRREL)

The Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire and Anchorage and Fairbanks, Alaska is part of the US Army Corps of Engineers Engineer Research and Development Center (ERDC). CRREL's overall mission is to solve interdisplinary, strategically important problems of the US Army Corps of Engineers, Army, Department of Defense, and the Nation by advancing and applying science and engineering to complex environments, materials, and processes in all seasons and climates, with unique core competencies related to the Earth's cold regions.

CRREL researchers lead and participate in a wide range of Arctic ice research programs, which are largely funded by outside agencies. These programs range from field observations, to process studies, to model development, and involve both basic and applied research. Area of expertise include sea ice research; snow/ice physics; icing on ships and fixed structures; permafrost research; oil-in-ice (detection & mitigation); and cold regions infrastructure.

Recent examples of CRREL Arctic ice research projects include:

Observations - Sea ice thickness in support of airborne and satellite instrument development; IMB & SIMB Buoys (sea ice mass balance); O-buoy (chemical sensors); spectral reflectance and transmission of solar radiation; melt pond evolution; floe size distribution; airborne ISR radar; satellite- based assessments of snow covered area (SCA) and snow water equivalent (SWE) for national and international regions

Process studies - Radiative transfer of solar radiation by snow and sea ice; heat and mass balance of sea ice; ice forces on structures; ice floe forecasting; icing on structures

Computer simulation - Discrete Element Modeling (DEM) of sea ice (force and movement)

Cold regions engineering - Autonomous observing platforms; Engineering for Polar Operations, Logistics, and Research (EPOLAR); remote snow assessments; National snow loads building standards; National ice loads building standards

CRREL is also home to a unique set of refrigerated research facilities. While housed on a government campus, these facilities are widely available to other government, academic and privately owned agencies. For example, in recent years CRREL has hosted a consortium projects to advance the capability of detecting oil in ice covered waters.

United States Interagency Arctic Buoy Program (USIABP)

The USIABP/IABP maintains a network of autonomous buoys on the Arctic Ocean, which provide meteorological and oceanographic data for real-time operational requirements and research purposes including support to the World Climate Research Programme, the World Weather Watch Programme, and the Arctic Observing Network (AON).

The observations from the IABP have been essential for: 1.) Monitoring Arctic and global climate change (many of the changes in Arctic climate were first observed or explained using data from the IABP); 2.) Forecasting weather and sea ice conditions; 3.) Forcing, assimilation and validation of global weather and climate models; 4.) Validation of satellite derived estimates of sea ice motion, surface temperature, sea ice thickness, etc.

The IABP is composed of 32 different research and operational institutions from many different countries. The IABP is funded and managed by the Participants of the program. The United States contribution to the IABP is coordinated through the United States Interagency Arctic Buoy Program (USIABP), which is managed by the National Ice Center and the Polar Science Center, Applied Physics Laboratory, University of Washington. The USIABP is a collaborative program that draws operating funds and services from a number of U.S. government organizations and research programs, and industry. From these contributions the USIABP acquires and deploys buoys on the Arctic

Ocean, and supports the Coordination, Data Management and Enhancement for the IABP by the PSC/APL.

These data are available for research from http://iabp.apl.washington.edu, and posted on the WMO/IOC Global Telecommunications System for operational weather and ice forecasting. Data from buoys are available from 1979 to present, but the IABP also provides data from AIDJEX (1972 – 1976), and many of the manned drifting stations from their server.

Alaska Ocean Observing System (AOOS)
The mission of AOOS is to address regional and national needs for ocean information, gather specific data on key coastal and ocean variables, and ensure timely and sustained dissemination and availability of these data.

The Arctic is a team effort. As with our efforts statewide, AOOS work in the Arctic builds upon existing efforts and focuses on collaboration to increase the amount of real-time observations. The Arctic is changing with the climate, bringing with it the potential for increased commercial activity and major habitat changes for its permanent residents. AOOS:

- Host a centralized data clearing house with web-based tools and data products
- Work with marine users to fill gaps in ocean monitoring
- Foster collaborations to meet multiple stakeholder needs
- Maintains
    - 8 weather stations in Prince William Sound & 1 in Cook Inlet, streaming weather data and webcams
    - Wind (WRF) and circulation (ROMS) forecasts in Prince William Sound and Cook Inlet, & validating hydrological model in PWS
    - Cook Inlet wave buoy, providing real time sea conditions to mariners & forecasters
    - High Frequency radars in Chukchi Sea to monitor surface currents
- Supports
    - Deployment of seasonal wave buoy in Bering Sea
- Collaborates
    - With the Marine Exchange of Alaska to implement Automatic Identification System (AIS) transmitters to disseminate real-time weather data, buoy data, and weather forecasts to vessels
- Created Alaska Harbor Observation Network (AHON) with Seward and Kodiak stations: stream weather & web cams at harbors
- Funded ice radar installation in Barrow to monitor Arctic sea ice, now maintained with other funding
- Facilitating working group to increase sea level rise observations for western AK
- Developing archived website for coastal beach profiles
- Support tide gauge in Bristol Bay

- Maintains Cook Inlet and Bering Sea wave buoys
- Contributes funding to the Seward Line in the Gulf of Alaska, providing a critical long-term data series & climate trends twice per year on oceanographic conditions
- Maintains an underwater autonomous glider to monitor ocean conditions and water flow in the Arctic: will test hydrophone to record marine mammal calls
- Supports statewide ocean acidification monitoring by sampling for OA along the Seward Line, and contributing to a consortium supporting OA moorings in the Gulf of Alaska, Bering Sea, and Arctic
- Develops and maintains an electronic sea ice atlas showing weekly sea ice since the 1850s to the present
- Partnering with NOAA to collect oceanographic data along transects in Kachemak Bay and lower Cook Inlet to support new circulation forecast model and understand ocean acidification.
- Facilitating development of new animal tagging network in ArcticSupport ocean acidification monitoring network and developing Gulf of AK OA forecast
- Maintains AOOS website and data portal
    - Real-time Sensor Map
    - Model Explorer
    - Research Assets Map
    - Arctic Data Portal
    - Cook Inlet Response Tool
    - Research Workspace
    - Seabird Portal
    - Herring Portal
    - Industry Arctic Data

Office of Naval Research (ONR)

The Office of Naval Research Arctic and Global Prediction Program is motivated by the rapid decline in summer ice extent that has occurred in recent years. This has prompted renewed Department of Navy interest in understanding and predicting the Arctic physical environment at a variety of time and space scales. The ability to predict the location of the ice edge, the space-time evolution of the ice cover, and the ice thickness will be particularly critical to safe naval operations in the Arctic. To achieve this, models integrating the ocean, waves, ice and atmosphere must be able to represent the physical processes, interactions and feedbacks involved in the seasonal evolution of ice extent, area, thickness and volume. Consequently, the program has three focus areas:

- Developing integrated ocean-ice-wave-atmosphere Earth System models for improved prediction at a variety of time scales
- Improving understanding of the physical environment and processes in the Arctic Ocean
- Investigating new technologies, e.g., sensors, platforms and communications, for sustained operation and observation in the challenging Arctic environment

The Arctic and Global Prediction Program is committed to contributing to Navy STEM (Science, Technology and Mathematics) education efforts, particularly the education of the next generation of scientists specializing in the physics of the Arctic Ocean system.

Current Research

Coordination, Data Management and Enhancement of the International Arctic Buoy Programme: A US Inter-agency Arctic Buoy Programme (USIABP) Contribution to IABP - ONR is one of a number of agencies (NSF, NOAA, NASA, Navy) that support the US Arctic Buoy Program, which has been observing sea ice drift via buoys for over 30 years.

Radar Remote Sensing of Ice and Sea State and Boundary Layer Physics in the Marginal Ice Zone - An additional "science" marine radar will be installed on the R/V Sikuliaq to support an investigation of waves and swell in open water and in the sea ice cover. This investigation is part of a larger ONR study of "Sea State and Boundary Layer Physics of the Emerging Arctic Ocean"; the main field experiment will be in early autumn 2015. The results of the marine radar and waves in ice study are likely to provide insights into the issue of ice detection and classificationby marine radar. For more information about the "Sea State"project, go to http://www.apl.washington.edu/project/project.php?id=arctic_sea_state

Waves and Fetch in the Marginal Ice Zone - As part of the ONR "Marginal Ice Zone" project, AWACs (Acoustic Wave and Current Profiler) were mounted on two moorings in the Canada Basin to measure waves in the ice cover and at the ocean surface once the ice has retreated in the summer. A spin off is sea ice draft and underwater profile information. For more information about the Marginal Ice Zone project, go to http://www.apl.washington.edu/project/project.php?id=miz

SCICEX: Inter-agency Arctic Navy Submarine Science Program - The US Navy has been releasing declassified sea ice draft data derived from upward-looking sonars mounted on submarines operating in the Arctic Ocean since the late 1950s. The data are available at the National Snow and Ice Data Center SCICEX Web site: http://nsidc.org/scicex/. Many of the data sets have been processed at the University of Washington, Applied Physics Laboratory.

Evolution of the Marginal Ice Zone: Adaptive Sampling with Autonomous Gliders - Seagliders have been deployed in the Beaufort Sea as part of the ONR "Marginal Ice Zone" project. They will obtain water temperature and salinity, microstructure and bio-optical data as they undertake surveys between late July and late September 2014. All data will be stamped with GPS positions obtained from a network of acoustic sources, which will also send adaptive sampling instructions to the gliders - see entry on acoustic communications and navigation below. Data are stored aboard the floats until they are able to surface and communicate via Iridium.

Autonomous Profiling Float Measurements of the Ocean Stratification Field - As part of the ONR "Marginal Ice Zone" project, eight polar profiling floats were deployed in March 2014 under the ice of the eastern Beaufort Sea. They are free drifters making water temperature and salinity measurements. All data will be stamped with GPS positions obtained from a network of acoustic sources - see entry on acoustic communications and navigation below. Data are stored aboard the floats until they are able to surface and communicate via Iridium.

Wave Gliders for Arctic MIZ Surface Observations and Navigation Support - As part of the ONR "Marginal Ice Zone" project, two Wavegliders, each equipped with an automatic weather station and an underwater acoustic source, were deployed in the Beaufort Sea in late July 2014. The acoustic sources supplement an array of sources deployed in March 2014. See next entry forinformation about the acoustic sources. The Wavegliders will be recovered in late September.

Acoustic Communications and Navigation for Mobile Under-ice Sensors - Eight acoustic sources (25 Hz bandwidth, 900 Hz carrier, 183 dB SPL) were deployed in the eastern Beaufort Sea in March 2014. Suspended ~100 m below the ice, the sources provide communications and navigation services to eight polar profiling floats and four Seagliders (see above).

LDUUV - Large Displacement Unmanned Undersea Vehicle - The LDUUV is an Innovative Naval Prototype (INP) for a reliable, fully autonomous, long endurance UUV capable of extended operation (60+ days). The LDUUV might be tested in Arctic waters.

MIZMAS (Marginal Ice Zone Modelling and Assimilation System): Modeling the Evolution of Ice Thickness and Floe Size Distributions in the Marginal Ice Zone of the Chukchi and Beaufort Seas - MIZMAS is being developed as part of the ONR Marginal Ice Zone project. It is primarily a process model derived from PIOMAS (Pan-Arctic Ice and Ocean Modelling and Assimilation System), but is also being used for forecasting the drift of the MIZ instrument array deployed in March 2014 in the eastern Beaufort Sea. Such forecasts aid remote sensing data collections and field operation planning.

ACNFS: Arctic Cap Nowcast/Forecast System - Not strictly an ONR activity, the ACNFS is being used to forecast the drift of the ONR Marginal Ice Zone project instrument array deployed in March 2014 in the eastern Beaufort Sea. Such forecasts aid remote sensing data collections and field operation planning. ACNFS is the U.S. Navy operational model for nowcasting and forecasting Northern Hemisphere ice concentration and ice edge location. For more information go to http://www7320.nrlssc.navy.mil/hycomARC/

Wave-ice interaction in the Marginal Ice Zone: Toward a wave-ocean-ice coupled modeling system - Part of the ONR "Sea State and Boundary Layer Physics" project, this investigation aims to (1) improve the physics of wave-ice interactions in

WAVEWATCH-III, an operational wave forecast model, and (2) add waves to the ACNFS (see above). This will improve forecasting of waves, and the ice edge, ice concentration and ice drift.

Optimizing Observations of Sea Ice Thickness and Snow Depth in the Arctic - A 9-km-long survey line was established on the sea ice near the US Navy ICEX2011 ice camp in March 2011. It was strategically located to cover a wide range of ice types, including refrozen leads, deformed and undeformed first year ice, and multiyear ice. A highly concentrated set of in situ measurements of snow depth and ice thickness was taken along the survey line. Once the survey line was in place, NASA IceBridge flew a dedicated mission along the survey line, collecting data with an instrument suite that included the Airborne Topographic Mapper (ATM), a high precision, airborne scanning laser altimeter; the Digital Mapping System (DMS), a nadir viewing digital camera; the University of Kansas ultrawideband Frequency Modulated Continuous Wave (FMCW) snow radar; and the University of Kansas Ku-band radar-altimeter. NRL also conducted a dedicated airborne mission using a complementary suite of sensors that included a radar altimeter, LiDAR and photogrammetric camera. In addition to quantifying measurement errors , the results will also be applied to improve understanding of new sensors such as (i) the NRL radar altimeter, (ii) the IceBridge snow radar, and (iii) the European Space Agency (ESA) CryoSat-2 satellite carrying the new state-of-the-art SIRAL radar altimeter.

The Role of Atmospheric, Ice and Oceanic Interactions in the MIZ - This project includes the use of synthetic aperture radar (SAR) images (RADARSAT-2, TerraSAR-X, COSMOS-Skymed) and declassified, high resolution, visible band images to determine sea ice floe size distributions in the marginal ice zone.

Tracking and Predicting Fine Scale Sea Ice Motion by Constructing Super-Resolution Images and Fusing Multiple Satellite Sensors - This project involves tracking fine-scale sea ice motion from super-resolution images created by fusion of lower resolution MODIS and passive microwave data, and using a Hidden Markov Model to predict fine scale sea ice motion based on the remotely-sensed ice motion.

Developing Remote Sensing Capabilities for Meter-scale Sea Ice Properties - Melt pond area fraction, floe size distribution and ice surface roughness will be tracked through time and space using high resolution satellite multispectral optical (Quickbird, Worldview), panchromatic optical (National Technical Means) and synthetic aperture radar (SAR: TerraSAR-X, COSMO-SkyMed, and RADARSAT-2) data.

Operationally merged satellite visible/IR and passive microwave sea ice information for improved sea ice forecasts and ship routing - MODIS and AMSR-E passive microwave data are merged to produce an improved, all-season ice concentration and ice edge product for assimilation into the U.S. Navy ACNFS (Arctic Cap Nowcast/Forecast System) operational forecast model. Initial test show that the merged product improves ice edge forecasts by as much as 17% compared to assimilation of AMSR-E data alone.

Wave Processes in Arctic Seas Observed from TerraSAR-X - Existing TerraSAR-X wave parameter and ice motion retrieval algorithms will be adapted for use in the marginal ice zone in order to analyze the spatial and temporal variability of the wave field in the emerging ice-free regions; investigate wave damping in sea ice and related ice break up; test/develop formulae of wave development (such as fetch laws) for the marginal ice zone; derive ice motion in the marginal ice zone.

Applying High Resolution Imagery To Understand The Role Of Dynamics In The Diminishing Arctic Sea Ice Cover - This project aims for a comprehensive insight into the role of sea ice dynamics and kinematics, including divergence and shear, as driving forces for changes in the sea ice cover. The primary data source will be declassified, high resolution, visible band images, supplemented by NASA Operation IceBridge sea ice products, MODIS and AVHRR data, and satellite altimetry (ICESat, Cryosat-2) products to measure ice floe, lead and ridge size distributions, and ice thickness distributions.

National Atmospheric and Space Administration (NASA)

NASA has established the following objectives for Arctic sea ice:

- To improve our understanding of the mechanisms controlling sea ice cover, including interactions with the ocean and atmosphere.
- To develop, validate and improve predictive models of changes in sea ice cover, and their implications for the Earth system.
- To improve estimates of snow accumulation on sea ice.

NASA develops, launches, and operates satellite missions (e.g., ICESat-2, Aqua, Terra, etc), and conducts airborne campaigns to supports the above objectives. Examples include the on-going Operation IceBridge mission and the development of the ICESat-2 mission with one of the primary science objectives to map the thickness of the sea ice cover.

For scientific investigations, the Cryospheric Science Program is charged to provide:

- Funding and oversight of cryosphere-related scientific studies at universities, NASA centers and other institutions.
- Support to cryosphere-related satellite mission Science Teams (e.g., ICESat-2, GRACE, Aqua, Terra, etc.)
- Support for the collection of cryosphere-related observations through the Airborne Sciences Program (e.g., Operation IceBridge).
- Investment in the development of satellite and airborne cryosphere-related data sets, including storage and distribution capabilities.

In addition, the program sponsors several polar initiatives designed to encourage interdisciplinary approaches to cryospheric science problems (e.g., Program for Arctic Regional Climate Assessment (PARCA).)

Furthermore, NASA works closely with interagency partners, especially the NSF's Office of Polar Programs, the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DoD), the U.S. Army Cold Regions Research and Now, with long-term observations available from satellites and aircraft, better understanding of key relationships within the Earth system, and continual improvements in remote-sensing technologies, Engineering Laboratory (CRREL), and the United States Geologic Survey (USGS).

INTERNATIONAL COOPERATIVES

One of goals in the National Arctic Strategy is to strengthen international cooperation, which is interpreted to include research partnerships. While the US Arctic is influenced by the pan-Arctic environment, and the pan-Arctic is part of the larger global system, only programs conducted in the US are included in the topic paper.

RUSALCA

July 23, 2004 marked an historic day in Arctic research and exploration as well as Russian-U.S. relations. On this date the Russian research ship, the Professor Khromov, left Vladivostok, Russia packed with U.S.and Russian, funded scientists to begin a 45-day collaborative journey of exploration and research in the Arctic.

Stemming from a 2003 Memorandum of Understanding for World Ocean and Polar Regions Studies between NOAA and the Russian Academy of Sciences, this cruise was the first activity under the Russian-American Long-term Census of the Arctic (RUSALCA). RUSALCA means mermaid in the Russian language. In November 2003, a RUSALCA planning workshop was held in Moscow, Russia to outline the biological, geological, chemical and physical oceanographic sampling strategies to be pursued in the Bering Strait and the Chukchi Sea.

The Initial Expedition to the Bering and Chukchi Seas (Arctic Ocean), was conducted July 23 – September 6, 2004. This initial cruise was a collaborative U.S – Russian Federation oceanographic expedition to the Arctic seas regions shared by both countries: the Bering and Chukchi Seas. These seas and the life within are thought to be particularly sensitive to global climate change because they are centers where steep thermohaline and nutrient gradients in the ocean coincide with steep thermal gradients in the atmosphere. The Bering Strait acts as the only Pacific gateway into and out of the Arctic Ocean and as such is critical for the flux of heat between the Arctic and the rest of the world. Monitoring the flux of fresh and salt water as well as establishing benchmark information about the distribution and migration patterns of the life in these seas are also critical pieces of information needed prior to the placement of a climate-monitoring network in this region.

ACADEMIC PROGRAMS

University of Alaska – Fairbanks (UAF)
The University of Alaska Fairbanks has a long history of sea ice research in Alaska and UAF made numerous contributions to the research efforts of OCSEAP, AIDJEX and other research programs described in this section. Here we summarize UAF's research activities in the Chukchi and Beaufort Seas over the last 15 years.

Barrow sea ice observatory (1999-present) - UAF maintains a number of sea ice monitoring activities in Barrow that support a broad research program including studies of ice growth and melt processes [Grenfell et al., 2006; Mahoney et al., 2009], landfast sea ice dynamics [Mahoney et al., 2007; Druckenmiller et al., 2009; Jones, 2013], break-up forecasting [Petrich et al., 2012a], human-sea ice interactions [Eicken et al., 2009; Druckenmiller et al., 2010; Eicken et al., 2011; Gearheard et al., 2013] and range of biological and ecological studies [Meiners et al., 2008; Gradinger et al., 2009; Manes and Gradinger, 2009; Petrich et al., 2012b]. The principal components of the UAF's Barrow sea ice observatory include:

- Sea ice mass balance program (1999-present): Annual timeseries of the growth, ablation and temperature profile of landfast sea ice and snow. Near-real time and archived data available at http://seaice.alaska.edu/gi/observatories/barrow_sealevel
- Ice coring (1999-present): Data from multiple cores collected from landfast ice and pack near Barrow are available at http://seaice.alaska.edu/gi/data/barrow_icecore.
- Coastal web cam (1999-present): A near-continuous record of images stored every 5 minutes from a webcam overlooking the coast. The current image and archive time-lapse animations are available at http://seaice.alaska.edu/gi/observatories/barrow_webcam)
- Coastal sea ice radar (2003-present): Digital radar imagery allowing detection and tracking of sea ice out to a range of approximately 10 km from the coast can be found at: http://seaice.alaska.edu/gi/observatories/barrow_radar
- Local sea ice observations (2006-present): Inupiaq and Yupik sea-ice experts have contributed observations on ice conditions, ice hazards and ice use since fall 2006. In a collaboration between SIZONet and ELOKA these obervations have been compiled into a database for sharing with coastal communities and researchers (Eicken et al. 2014).

Experts Workshops to Comparatively Evaluate Coastal Currents and Ice Movement in the Northeastern Chukchi Sea - In light of increased industrial activities in United States Arctic offshore waters, effective response to spills of oil and hazardous substances in coastal, seasonally ice-covered waters is universally recognized as a critical challenge to sustainable development in northern Alaska. Due to limited in-situ and remote sensing observations, current and ice motion patterns in coastal settings are poorly understood. To address this shortcoming, workshops held in March 2013 in Barrow and Wainwright, Alaska, focused on nearshore ice and ocean currents of the coastal Chukchi and Beaufort Seas. Indigenous experts from Barrow, Wainwright, Point Lay, and Nuiqsut

met with scientists from the University of Alaska Fairbanks and other institutions to discuss ice conditions and ocean circulation and to identify the knowledge critical to emergency preparedness and response.

The report informs agencies about coastal Chukchi and Beaufort Sea ice and ocean circulation, seasonal freezing, ocean access, and local expertise. Workshop recommendations call for measurements in new places and at specific times of year to improve our understanding of nearshore ice and ocean current variability and seasonality.

Local and indigenous experts described ice and ocean features, often using Iñupiaq terms. Whalers and hunters learn from elders and by experience under conditions critical to success and survival. Local knowledge at the scale related to hunting and travel experience is rich in detail and complements the typically larger scales of remote sensing and ice-ocean models.

Local experts heard scientists with expertise in sea ice and physical oceanography describe remote forcing and local water and ice dynamics. Shared knowledge broadened the collective understanding of coastal currents, river and lagoon freeze-up, nearshore freezing, and ocean circulation of the Chukchi Sea and Beaufort Sea barrier islands.

Recommendations from the workshops include follow-up studies that will:

- Compare observed convergence locations with trajectory model results,
- Document ice seasonality including slush ice formation and shoreline freezing,
- Identify emergency shoreline staging locations and barrier island access points,
- Measure current speed and direction near jets, fronts, and shear zones,
- Provide real-time tracking for sizable drift ice (e.g., multi-year or glacial floes),
- Extend ocean wave measurements into freeze-up,
- Continue high-frequency radar coverage and buoy studies,
- Continue to reconcile disparities between the frames of reference, scales of observation, and vocabularies that exist between local experts and scientists when discussing ice and ocean observations.

Seasonal ice zone observing Network (SIZONET; 2007-2014) - The Seasonal Ice Zone Observing Network (SIZONet) is an interdisciplinary NSF-funded project that implements an integrated program of seasonal sea ice observations in the context of sweeping environmental, (geo)political and socio-economic change in the North. In addition to sampling of sea-ice state variables, the observation-system design is guided by the concept of sea-ice system services (SISS). By assessing the nature and extent of SISS, an integrated observation network can be built that will lead to prediction of key trends in a changing Arctic in a way that provides maximum benefit for the broadest range of affected interests. In addition to the Barrow Sea Ice observatory described above, SIZONet is comprised of a number of other inter-connected components:

- Airborne sea ice thickness surveys (2007-2014): Data from annual campaigns to measure sea ice thickness using electromagnetic (EM) techniques are available through the Advanced Cooperative Arctic Data and Information Service (ACADIS).
- Under-ice oceanographic mooring data (2009-present): continuous timeseries of under-ice temperature, salinity and ocean currents at two mooring locations near Barrow are also available through ACADIS. As of this writing, coincident ice draft measurements from ice profiling sonars (IPSs) are currently undergoing final processing.

Leads and landfast ice mapping (1994-2010) - UAF has led a comprehensive analysis of leads and landfast ice the Chukchi and Beaufort Seas relevant for offshore development activities. The final report and associated datasets (available at http://boem.gina.alaska.edu) provide GIS-ready grids of AVHRR-derived lead patterns and Radarsat-derived landfast sea ice extent as well as monthly climatologies. A recent paper by Mahoney *et al.* [2014] presents a detailed summary the landfast ice data including an assessement of multidecadal trends.

Entrainment of oil into sea ice and potential impacts on ice biota - In a collaboration between sea-ice biologists and geophysicists (supported by the Coastal Marine Institute), indoor tank experiments, coupled to in-situ sampling in Barrow, Alaska, are being carried out at UAF to quantify and simulate key constraints on entrainment and percolation of oil in sea ice and its impact on ice bacteria, microalgae and zooplankton.

Polar Science Center, Applied Physics Lab, University of Washington (PSC/APL/UW)

The Polar Science Center (PSC, http://psc.apl.washington.edu) grew out of the group of researchers that came together as part of a multi year Arctic Ice Dynamics Joint Experiment (AIDJEX). The PSC conducts basic and applied research on the oceanography, climatology, meteorology, biology and ecology of the ice-covered regions on Earth and elsewhere in our solar system . The scope of PSC research and fieldwork includes the Arctic and the Antarctic, as well as sea-ice, glaciers and continental ice sheets. The PSC is a department of the Applied Physics Laboratory (APL, http://www.apl.washington.edu) at the University of Washington. The PSC projects in the Beaufort and Chukchi seas include:

APL Ice Station (APLIS) – The APL establishes an arctic ice camp on an ice floe in the Beaufort Sea to support U.S. Navy and civilian personnel every 2 – 3 years. For about a month in March, when temperatures were as low as –40°C, engineers from APL and Navy personnel conducted under-ice exercises (ICEX) with submarines on site. The APLIS stations usually allow research and field work after ICEX. The most recent APLIS was occurred in 2014, and plans are underway for a camp in 2016.

Biology and Climate Change - PSC researchers conduct Arctic biological research, ranging from studies that aim to understand how microscopic life exists at low temperatures to studies that aim to understand the migration patterns and feeding habits of polar bears and whales. We are also developing computer models to track and predict future changes in Arctic ecosystems.

Bering Sea: Pacific Gateway to the Arctic - The Bering Strait is the only Pacific gateway to the Arctic Ocean. Waters flowing through the strait are a key source of nutrients, heat and freshwater for the Arctic. Since 1990, PSC has measured the properties of this throughflow using long-term in situ moorings, supported by annual cruises.

Marginal Ice Zone Project - Recent decades have seen pronounced Arctic warming accompanied by significant reductions in sea ice volume and a dramatic increase in summer open water area. The resulting combination of increased ice-free area and more mobile ice cover has led to dramatic shifts in the processes that govern atmosphere–ice–ocean interactions, with profound impacts on upper ocean structure and sea ice evolution. The summer sea ice retreat and resulting emergence of a seasonal marginal ice zone (MIZ) in the Beaufort Sea exemplifies these changes and provides an excellent laboratory for studying the underlying physics. See http://www.apl.washington.edu/project/project.php?id=miz.

Numerical Modeling of the Arctic Ocean - PSC is one of the leading institutions for numerical modeling of the Arctic Ocean. hese models, when compared to observations, allow us to test our understanding of the physical and biological processes in the polar oceans. They also let us make predictions of potential future changes on seasonal, interannual, and decadal time scales. PSC is a world leader in ice–ocean modeling. The Pan-arctic Ice Ocean Modeling and Assimilation System (PIOMAS) is a workhorse applied to many of our studies. The Global Ice Ocean Modeling and Assimilation System (GIOMAS) is used to investigate both the Arctic Ocean and the Southern Ocean. The Bering Ecosystem Study ice–ocean Modeling and Assimilation System (BESTMAS) is used for high-resolution studies of the Bering Sea. Our ice–ocean modeling system has been expanded to model biological processes including primary production, nutrient cycling, and plankton functioning (the Biology/Ice/Ocean Modeling and Assimilation System, BIOMAS). Our atmospheric modeling team is using the Weather Research and Forecast Model (WRF) to examine the impact of sea ice changes on clouds, precipitation and the distribution of heat within the Arctic.

Seasonal Ice Zone Reconnaissance Surveys The purpose of this project is coordination of repeated ocean, ice, and atmospheric measurements across the Beaufort-Chukchi sea seasonal sea ice zone (SIZ) utilizing US Coast Guard Arctic Domain Awareness (ADA) flights of opportunity. SIZRS, like the ONR Arctic and Global Prediction Program, is motivated by the rapid decline in summer ice extent that has occurred in recent years. The SIZ is the region between maximum winter sea ice extent and minimum summer sea ice extent. As such, it contains the full range of positions of the marginal ice zone (MIZ)

where sea ice interacts with open water. The increasing size and changing air-ice-ocean properties of the SIZ are central to recent reductions in Arctic sea ice extent. To understand the changes in the interplay among the ice, atmosphere, and ocean requires a combined systematic observational and modeling effort, covering up to interannual time-scales. We will integrate the SIZ Reconnaissance Surveys (SIZRS) results with models and other in situ and remote sensing observations to better understand and predict air, sea, and sea ice conditions in the Beaufort/Chukchi SIZ (BCSIZ), a region that is showing substantial interannual change.

US Interagency Arctic Buoy Program, and International Arctic Buoy Programme (IABP) - The participants of the IABP work together to maintain a network of drifting buoys in the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes including support to the World Climate Research Programme and the World Weather Watch Programme. The U.S. contributions to the IABP are coordinated through the USIABP, which is managed by the U.S. National/Naval Ice Center, and the Polar Science Center, and represent several U.S. agencies. See http://iabp.apl.washington.edu.

Woods Hole Oceanographic Institution (WHOI)
Despite its remoteness, the Arctic Ocean is intimately connected to the health of the planet, because it plays a pivotal role in Earth's climate system. The reality of recent changes in the Arctic—rapid warming and the accelerating loss of sea ice—is now widely acknowledged. The impact of such changes on marine and terrestrial ecosystems in the Arctic and beyond will be profound. Yet, research in the Arctic is complicated and difficult, because it is a largely inaccessible and unforgiving environment.

Growing interest in conducting such challenging research led WHOI to establish the Arctic Research Initiative.

The initiative includes support for:

- Field programs to monitor changes in ocean circulation and sea ice,
- Studies of river flow and the chemical composition of the waters draining into the Arctic Ocean,
- Investigations of melting permafrost surrounding the Arctic Ocean and glaciers on the Greenland ice sheet,
- Measurements of nutrient and carbon transport from the land to the sea,
- Assessing changes in the ecosystem for marine mammals and resulting effects on local indigenous populations,
- Gauging the impacts of increased coastal erosion and
- Development of new remote monitoring systems to observe this challenging environment.

Ocean circulation plays a key role in moderating the global climate, and the presence or absence of sea ice, permafrost, and glaciers impacts that circulation—thus, climate well beyond the Arctic. As climate changes, ecosystems change, and their inhabitants either adapt, move, or expire.

Therefore, the broad questions addressed by this initiative are:

- What are the regional and global effects of changes in the Arctic on the extent of sea ice, on ocean circulation, and on climate?
- What are the current and likely future effects on ecosystems within and beyond the Arctic? Understanding the changes in the Arctic will enable us to predict changes elsewhere in the world and perhaps indicate ways in which we might mitigate or cope with future climate change.

Current Research

Beaufort Gyre Exploration Project - Ice, ocean, atmosphere. These three components constitute the health of the Arctic climate. At the heart of this system is one of the least studied bodies of water on the planet: the Beaufort Gyre, a slowly swirling bowl of icy water north of Alaska ten times the size of Lake Michigan.

Recent observations suggest that because of global warming, the natural rhythms of the Beaufort Gyre have been tipped out of balance. To find out what this means for the future of the Arctic climate, scientists from the United States, Canada, and Japan will set out every summer from 2003 to 2014 for month-long expeditions aboard the Canadian icebreaker Louis S. St-Laurent. They are using an array of newly-developed instruments to measure the environment above, below, and within the floating icepack.

Byrd Polar Research Center - Ohio State University
Named in honor of one of America's most famous explorers, the Byrd Polar Research Center of The Ohio State University is recognized internationally as a leader in polar and alpine research. The Center's research programs are conducted throughout the world.

Research at the Center focuses on the role of cold regions in the global climate system, with major themes focused on:

- Climatic reconstruction of glacial and post-glacial times;
- Polar ice-sheets: dynamics, history and ice-atmosphere interactions;
- High-latitude landform evolution, soils and hydrology;geologic evolution of Antarctica;
- Investigations of ocean dynamics and environmental-chemical processes;
- And the history of polar exploration.

Scientists at the Byrd Center are reconstructing past climate by studying chemical records preserved in ice cores collected from glaciers in Greenland, Asia, North and South America, and Antarctica. Fossils provide important evidence for much older changes in climate and plant fossils collected in the Transantarctic Mountains indicate that parts of the southern continent were once forested. Environmental studies include programs in Alaska and Russia which are concerned with hydrologic and geochemical cycles in permafrost terrains and interactions with the biosphere. Modern processes such as the motion of the great ice sheets and the circulation of storm systems around Antarctica are being studied with sophisticated computer models and with satellite-borne sensors capable of imaging the surface through cloud cover and during the long polar night.

The Center has an archival program which is a collaborative effort of the Center and The Ohio State University Libraries/Archives. Our Education Outreach program provides publicly-accessible information about our research to schools in the local area and around the world, public interaction with scientists, and hosts group tours, public events, and sponsorships.

University of Illinois at Urbana-Champaign (UIUC)

The Department of Atmospheric Sciences is engaged in a variety of studies to unravel the nature of climate variability in the Arctic. Students have used models to address the reasons for changes in the Arctic Ocean and its sea ice cover, and the latest output from the major climate models of the world is being used to distinguish natural and anthropogenic changes in the Arctic. The department participates actively in aircraft programs and satellite studies to gain a better understanding of the critical role played by clouds in Arctic climate. Students have studied wintertime cold waves and the Arctic wind patterns to understand better the connection between the Arctic and middle latitudes.[8] Arctic climate research is conducted using both observational and modeled approaches. A useful resource for ice area observations, trends, and statistics is the Cryosphere Today[9] website maintained by UIUC.

Current research includes: Arctic System Reanalysis, ERA40 Reanalysis, Arctic Climate Impact Assessment, Scenarios Network for Alaska Planning (SNAP), and analysis output used in the IPCC 4th Assessment Report.

Naval Postgraduate School (NPS)

The Pan-Arctic Region is an important area for global climate and Northern Hemisphere weather systems, both in terms of its effect on sea levels, ocean/atmosphere circulation and sensitivity as an indicator of warming trends. There is conclusive evidence to demonstrate that, since the late 1990s, melting of the perennial ice- cover in the Arctic has accelerated significantly, yet the exact mechanisms, causes and rates of this melt are still poorly understood. Interdisciplinary and multi-institutional studies led by Professor

[8] http://www.atmos.illinois.edu/research/04arctic.html
[9] http://arctic.atmos.uiuc.edu/cryosphere/

Wieslaw Maslowski at the Naval Postgraduate School (NPS) in Monterey, California, aim to advance understanding of the Arctic Climate System through rigorous, detailed and regional methodology.[10]

The research team is committed to novel technologies which increase the resolution and improve the representation of fine-scale processes and land-atmosphere-ice-ocean interactions to advance understanding and prediction of Arctic climate change.

Current Research

Regional Arctic System Model (RASM)
This project and several complementary projects grew out of regional Arctic climate modeling work at the Naval Postgraduate School, the University of Colorado, Iowa State University and the University of Washington. Currently, our team involves 30 researchers, including students, from 10 institutions, and this number is growing. Members from each institution have worked with stand-alone model components, such as ocean, ice, atmosphere and land models, and identified the need for a fully-coupled regional climate model that thoroughly explores the interactions between components. Objectives:

To develop and apply a regional Arctic System model to resolve small-scale processes and feedbacks as well as to realistically represent large-scale climate variability and trends
To advance understanding of past and present states of Arctic climate and to improve seasonal to decadal predictions

RASM will soon include ice sheets, ice caps, mountain glaciers, and dynamic vegetation. RASM allows high spatial resolution to represent critical processes and determine the need for their explicit representation in GC/ESMs.

The overarching goal of the project is to advance understanding of Arctic climate system operation and variability to improve model prediction of Arctic climate change at decadal to centennial scales. A set of specific objectives is proposed centered on the following main science hypothesis: Given the projections of continued global warming and its northern high-latitude amplification, the Arctic will become nearly ice-free during summer in the near future, resulting in altered physical state of and interconnections within the Arctic climate system.

To confirm or disprove the above hypothesis, our approach is to use subsets of model components and fully coupled RACM to address the following specific objectives:

[10] http://www.oc.nps.edu/NAME/ResearchMedia.EU_Maslowski_highres.pdf

- Identify potential improvements in the simulated sea ice thickness distribution and deformation due to increasing model resolution and representation of fine-scale ice-ocean interactions
- Investigate effects of shrinking and thinning sea ice on ice kinematics and its consequences on changing air-ice and ice-ocean interactions
- Examine and quantify consequences of melting sea ice on the increased upper ocean heat content and its potential for increased ice melt due to a positive ice-ocean feedback loop
- Assess the influence of excess oceanic heat release, especially in fall and winter, on potentially enhancing cyclonic tendency in the atmosphere
- Explore the importance of increased sea ice melt and runoff to the Arctic hydrological cycle and its acceleration in the context of first-year ice growth and survival
- Integrate positive and negative feedback processes into model simulations of warming climate scenario to determine their net impact on the long-term state of Arctic ice cover
- Identify physical and numerical requirements of future GCMs to significantly improve model skill in representing past and present and in predicting future Arctic climate change.

A hierarchy of well designed one-way and fully coupled regional climate system model experiments will focus on the above objectives. Such experiments will provide advanced insight into the behavior of the Arctic climate system that is not currently attainable using either individual regional component models or GCMs.

University of Colorado, Boulder

The Department of Atmospheric and Oceanic Sciences (ATOC) is an interdisciplinary program that provides an educational and research environment to examine the dynamical, physical, and chemical processes that occur in the atmosphere and the ocean. Graduate students, research staff, and faculty work together on a wide range of research topics: large-scale dynamics of the ocean and the atmosphere; air-sea interaction; radiative transfer and remote sensing of the ocean and the atmosphere; sea ice and its role in climate; cloud-climate interactions; atmospheric chemistry and aerosols; atmospheric technology; extended weather and climate prediction; hydrological processes; boundary layer measurement and modeling; and planetary atmospheres.

ATOC has extensive computer facilities and laboratories in remote sensing, chemistry, and hydrodynamics. Interdisciplinary research opportunities also exist with the Cooperative Institute for Environmental Studies (CIRES), the Institute for Arctic and Alpine Research (INSTAAR), and the Laboratory for Atmospheric and Space Physics (LASP). The presence of leading laboratories in the environmental sciences in Boulder, including the National Center for Atmospheric Research and the NOAA Environmental Research Laboratories, provides additional opportunities for a rich educational experience.

National Center for Atmospheric Research (NCAR)
The National Center for Atmospheric Research is a federally funded research and development center devoted to service, research and education in the atmospheric and related sciences. NCAR's mission is to understand the behavior of the atmosphere and related physical, biological and social systems; to support, enhance and extend the capabilities of the university community and the broader scientific community – nationally and internationally; and to foster transfer of knowledge and technology for the betterment of life on Earth. The National Science Foundation is NCAR's primary sponsor, with significant additional support provided by other U.S. government agencies, other national governments and the private sector.

Within NCAR are several laboratories and programs that have relevance to Arctic ice and climate research:

NCAR Earth Systems Laboratory (NESL) - NESL's Mission: To advance understanding of weather, climate, atmospheric composition and processes; to provide facility support to the wider community; and, to apply our research results to benefit society. Formed in 2010, the NCAR Earth System Laboratory brings together NCAR's major lines of scientific inquiry . Research within NESL is highly collaborative, with specialties focused in the following three research divisions:

- The Atmospheric Chemistry Division (ACD) explores the impact of chemistry on climate and air quality.
- The Climate & Global Dynamics Division (CGD) examines Earth's climate system, analyzing the observed environment and developing models capable of predicting the evolution of the climate system.
- The Mesoscale & Microscale Meteorology Division (MMM) seeks to further our understanding of key scientific questions in meteorology, with emphases on both understanding and forecasting weather as well as weather's relationship to climate.

Earth Observing Laboratory (EOL) - Formed in 2005, the Earth Observing Laboratory (EOL) is one of the five laboratories of NCAR, the National Science Foundation's Federally Funded Research and Development Center. As the successor of NCAR's Atmospheric Technology Division (ATD), the mission of EOL is to provide leadership in observing facilities, field project support as well as research and data services needed to advance the scientific understanding of the Earth system.

EOL manages the majority of NSF's Lower Atmospheric Observing Facilities (LAOF) and deploys them in support of observational field campaigns, ranging from single investigator projects to large complex campaigns that involve multiple investigators, agencies, and platforms, nationally and internationally. EOL deploys its systems for research by scientists from universities, NCAR, and government agencies, as well as for

education. An integral part of EOL's mission is to develop the next generation of LAOF and to provide management and archiving of data from past supported campaigns.

In order to ensure progress in the atmospheric sciences, EOL supports a wide-range of research areas within the Earth system science, ranging from microscale to mesoscale to climate process studies, and employs LAOF platforms and systems that reach from the surface of the Earth to the lower stratosphere and beyond.

Current Research

PacMARS - As seasonal sea ice declines in much of the Arctic and reached record minima in 2012, oil and gas exploration is increasing, and additional ship traffic is also using Bering Strait, perhaps a portend of changes to come if the Northern Sea Route along the north coast of Russia becomes a practical ice-free route between Asia and Europe, reducing shipping costs significantly. The Northwest Passage through the Canadian Arctic has also become ice-free several times in recent summers, a significant change. All of the Arctic countries, including Russia, the United States, Canada, and Denmark (Greenland) are exploring the limits of their arctic continental shelves in order to advance claims under the Law of the Sea Treaty.

Within this context of environmental and likely socio-economic changes, wildlife populations and human communities are adjusting to these shifts in seasonal sea ice coverage and climatic warming that has been much more obvious than at lower latitudes. Subsistence hunting patterns in the Arctic are changing, and it is also clear that many organisms, from plankton to top predators may be changing their migration and foraging patterns. Productivity is also forecast to change as sea ice declines and penetration of sunlight into open water increases.

The overall goal is to provide guidance for scientific research needs in the region, as well as to serve stakeholder needs for understanding this important ecosystem and its vulnerabilities.

INDUSTRY/PRIVATE/REGIONAL PROGRAMS

North Pacific Research Board (NPRB)

NPRB is interested in funding research that will further our understanding of the marine ecosystem in the Bering Strait and Arctic Ocean (especially the U.S. Chukchi and Beaufort seas). The first phase of the NPRB Arctic research program involves a synthesis of existing scientific and traditional knowledge of the Arctic marine ecosystem and an identification of research needs to help plan a potential upcoming research program that will likely be undertaken in cooperation with other organizations.

At its most recent board meeting, the North Pacific Research Board (NPRB) formalized its intention to commit $6 million towards the development of an integrated Arctic

research program. This allocation of additional funding represents NPRB's commitment to the region as a priority area for continued research.

NPRB's goal is to develop a cohesive and synthetic research program that advances understanding of the Arctic marine ecosystem. NPRB will target research that supports effective management, sustainable resource use, and ecosystem information needs. The geographic extent of the program may include the northern Bering Sea (i.e. north of St. Matthew Island), the Bering Strait, the Chukchi Sea and/or the Beaufort Sea. Potential areas of research might include:

- Ecosystem structure and processes, including energy pathways and production cycles, and their relationship to sea ice dynamics and advection patterns
- Species dynamics and interactions, including tropic linkages
- Projected shifts in distribution and phenology in the context of climate change
- The role of increased human activity on Arctic marine ecosystems
- The impact of ecological change on communities and ecosystem services

Shell Exploration and Production Company

Since 2005, Shell has conducted a comprehensive environmental research program in the Alaskan Arctic that includes ice and metocean studies in preparation and support of exploration and development activities. Several of these studies have developed into joint efforts with industry partners such as ConocoPhillips and StatOil and with Federal entities such as BSEE. Unlike many of the government-funded and academic research programs, which are often one-offs or of limited duration, these are either year-round or repetitive seasonal studies. Motivation for these studies comes from the need to develop operational and design criteria of the contemporary ice and metocean environment for safe and efficient operations in the Alaskan Arctic. In addition, they provide validation to hindcast model statistics and provide characterizations for environmental impact studies. A unique aspect of Shell's program is that it includes a region ice and weather forecast service operated in-house to provide customized high spatiotemporal resolution support to field operations and operational planners.

The value of these studies is not confined to the industry sponsors. In 2011, leadership from Shell, ConocoPhillips, and StatOil signed a Memorandum of Agreement with NOAA that outlined a framework for collaboration, communication, and information sharing and to promote scientific integrity through openness and transparency. The MOA serves as a basis for coordination between NOAA and the Industry Parties to maximize skills, knowledge and resources directed at studies and observations of physical and biological sciences in the US Arctic waters, and for sharing the resulting information produced from such studies and observations with the public. As a result, under the MOA, Shell and partners have released to NOAA archived measurement data predating the MOA, ongoing study data, near-real time observations, and internally produced sea ice charts.

Shell Ice and Weather Advisory Center - Shell developed and operates the Shell Ice and Weather Advisory Center (SIWAC), which is an integrated forecasting service tailored to the needs and demands of Shell's field operations in Alaska. Started in 2007, SIWAC has evolved to be the most comprehensive and focused ice and weather operation covering the offshore and coastal areas from the Gulf of Alaska to the Canadian Beaufort.

Nationally operated ice and weather forecasting offices are not chartered to supply the level of service and quality of products necessary to make effective and efficient operational decisions and ensure that the demanding safety standards required by Shell for personnel, environment, and assets are met. The products and services provided by SIWAC contribute valuable information for defining opportunity windows, logistical movements, and seasonal openings and closings. SIWAC was designed to meet these needs by employing a dedicated team of expert Arctic forecasters with unmatched access to tools and field data. These experts, available around the clock during the operational season, are fully integrated into the operations process and directly engage Shell leadership, project managers, planners, and field personnel, ensuring that forecast products and services are fit for purpose.

SIWAC consists of a team of full time Arctic-experienced forecasters that work in rotations 24/7 to provide continuous coverage for Shell during the operational season. In addition, there are numerous personnel who provide support services to the forecasters, such as satellite tasking, IT and web services, and research specialists. A core operational philosophy of the SIWAC program is that the ice and weather are intricately linked; therefore the ice and weather forecasters sit together and produce their respective products collaboratively.

There is a constant stream of information available to develop the detailed and frequent forecast products. Among this information is high resolution RADARSAT2 satellite imagery, which is unaffected by lack of sunlight or cloud cover. Strategically placed Metocean buoys are deployed seasonally in the Chukchi and Beaufort Seas to report near real time measurements of atmospheric and oceanic parameters such as winds and temperatures. A network of field observers placed on Shell operated vessels provide routine reporting of local weather, sea, and ice conditions. Position reporting buoys are deployed to track movement of the pack ice. And Shell co-sponsors an array of UAF-operated HF Radar sites that map the ocean currents over wide areas of the Beaufort and Chukchi Seas. Additionally, SIWAC accesses publically available data and products to advise forecasting such as MODIS and AVHRR satellite data, nationally operated weather stations, and numerical models.

Ice Profiling Sonars (IPS) – A program to measure ice keel and velocity data began in Camden Bay near the Shell prospect Sivulliq in the US Beaufort Sea in 2005, with later deployments including multiple sites in the Chukchi Sea and Harrison Bay. These deployments consist of a pair of moorings- one carrying an IPS and the other an Acoustic Doppler Current Profiler (ADCP) Together, these instruments record a time series of sea

surface deformations and directional data on the movement of ice and currents within the water column. Results from these measurements produce statistics of ice keel depth, drift, frequency, and horizontal extent and a record of non-directional waves during periods of open water.

Freeze-Up Study – Continuing work started in 1980, Coastal Frontiers and Vaudrey and Associates Incorporated has conducted freeze up studies of the Chukchi and Beaufort Seas to document ice conditions during freeze up, locate and map significant ice features (such as: multi-year ice, leads, polynyas, land fast ice extent, rubble fields, ridges, and ice pile ups) and compare recent years' ice reconnaissance to those observations from the 1980s. The study is conducted using satellite-based synthetic aperture radar and aerial overflights. This study is operated as a JIP and currently BSEE is a co-partner.

Overflood Study – As the offshore break up process approaches, the rivers that drain into the Beaufort and Chukchi Seas begin to flow. Since the sea ice and landfast ice are still largely intact, the river waters flood atop the sea ice and pool. Holes or weaknesses in the ice allow the pooled water to drain through the ice and the action of the flood waters can disturb the seabed. This scouring can promote damage to unprotected infrastructure, therefore knowledge of location and frequency of scour is important for design consideration. The study is conducted by Coastal Frontiers using satellite-based synthetic aperture radar and aerial overflights, however in recent years, the overflights have been less frequent.

Satellite-Tracked Ice Drift Beacons – Beginning in 2007, Shell has deployed satellite-tracked ice drift beacons in the Beaufort Sea to observe movement characteristics of the nearshore, shear, and pack ice zones. These data are necessary to inform structural design basis to the frequency, speed, and direction of ice movements. In 2013, the internally executed program was discontinued and financial support is now provided to the USIABP to perform an expanded winter ice monitoring program.

Ice Island JIP – A joint industry project (JIP) to monitor the Ellesmere Island Ice Shelves in order to track ice islands as they drift towards industry licenses was initiated in 2009. The JIP was a joint effort between three industry companies, the Canadian Ice Services, MMS (now BOEM) and the contractor. Monitoring of the Ellesmere Ice Shelf was performed by use of satellite imagery. Once a region of calved ice was detected, monitoring of its southward drift was performed by further satellite imagery analysis. When Ice Island targets came within the range of aircraft, satellite tracked buoys were deployed upon some of the larger features and the targets tracked as they passed through the Canadian and US Beaufort Seas.

In recent years, as the Ellesmere Island Ice Shelves have diminished in size, the supply of ice islands has decreased. Due to the lack of ice island targets and safety concerns (targets were too far from land) the deployment of satellite tracked beacons was not performed every year. The program is still active but now mainly concentrates upon monitoring ice shelf breakup and the scanning for ice island targets in southern regions.

Data obtained from the program is used to develop a database on ice island size, drift speed, and history (ice islands break into smaller sizes as they drift southwards).

Metocean Buoys – To gain better knowledge of the offshore metocean conditions in the operational areas of the Beaufort and Chukchi Seas and provide in-situ data to improve weather forecasting, Shell has deployed buoys during the open water period since 2008. These buoys measure wind speed and direction, air and surface water temperature, barometric pressure, and solar intensity. The program presently consists of an array of five buoys, with three buoys upgraded to include an ADCP for measuring the current profile in the water column and waves sensor.

Field Observations – As part of an expanded effort to improve weather forecasting performance, Shell formalized a process where field personnel were specifically trained to observe and report weather, sea, and ice conditions from the vessels operating under Shell contract during the operational season. After signing the Memorandum of Agreement with NOAA, the program was transitioned to the National Weather Service Anchorage Office for training and execution. Now the observers aboard Shell assets report directly to NOAA's Volunteer Observing Ship (VOS) program.

Traditional Knowledge

Traditional (or indigenous) and local knowledge (TLK) are relevant in the study of the ice environment for a number of reasons relevant in the context of this report. They can provide a long-term perspective on average and anomalous ice conditions as well as extreme ice events and hazards; inform field sampling and study design at the local level; and are relevant in the context of ice uses and adaptation to rapid climate change by Arctic coastal residents (Eicken, 2010). Here, we provide a brief summary of research recently completed or underway in the US Arctic that is relevant in such a context. Huntington et al. (2009) provide useful information on research methodologies and on successful approaches to collaboration with indigenous ice experts; Mahoney and Gearheard (2008) focus specifically on community-based measurements of key ice properties such as thickness and snow depth.

Studies of indigenous knowledge of the sea-ice environment have a long history, with Nelson's (1969) study at Wainwright, AK as a landmark in the field. Recent advances owe much to the International Polar Year (IPY) 2007-09, and in particular the international Siku – Sea Ice Knowledge and Use project, summarized in a volume edited by Krupnik et al. (2010), with several contributions from the U.S. Arctic. While much more focused locally, another important effort was the Barrow Symposium on Sea Ice that helped establish a common framework for discussing the sea-ice environment from a Western and Iñupiaq perspective (Huntington et al., 2001). From this meeting derives a study focusing on sea-ice hazards, such as ice break-out events, ice-push events and a general change in the stability of the shorefast ice, and on adaptations by the Iñupiaq hunting community to such decadal-scale change (George et al., 2004). Given the holistic

nature of indigenous knowledge, the work of Fienup-Riordan in collaboration with the Calista Elders Council in the Yukon-Kuskokwim Delta deserves special mention, since it presents a most comprehensive picture of sea-ice knowledge as embedded in traditional Yup'ik knowledge of the natural and spiritual world (Fienup-Riordan and Rearden, 2012).

Building on the successes of the IPY, parts of the Siku project led by the University of Alaska Fairbanks (UAF) have evolved into an ad-hoc but reasonably robust network of community-based observations of the ice environment by indigenous sea-ice experts in Alaska (Seasonal Ice Zone Observing Network, SIZONet). The approach of this work and first results from eight years of observations are summarized in a study by Eicken et al. (2014) that also describes the development of an adaptive database designed to house and share such observational data. At present over 4500 individual, near-daily observations of ice conditions, ice use, ice-associated fauna and ice hazards in key communities in the Bering and Chukchi Sea are housed in a database hosted and developed in collaboration with the Exchange for Local Observations and Knowledge of the Arctic (ELOKA; accessible at nsidc.org/data/eloka031). Observations include important dates in the annual sea-ice cycle such as freeze-up and break-up as well as in-depth reports of ice processes (such as formation of coastal ice berms, which have been identified as an important factor in protecting the shoreline during fall freeze-up; Eicken et al., 2014) and their impact on the community.

The Bering Sea Sub-Network (BSSN) is another IPY-derived project with some information on traditional knowledge of ice conditions, mostly in the context of community health and subsistence activities (Fidel et al., 2014). Along similar lines, though more comprehensive in coverage and firmly embedded within tribal government is the Alaska Native Tribal Health Consortium's Local Environmental Observer (LEO) network (www.anthc.org/chs/ces/climate/leo), which provides a framework for opportunistic observations of environmental phenomena of relevance in a community health context. Because of LEO's presence in many of the coastal communities in Alaska's Arctic and its link to funded Tribal Environmental Coordinator positions, it serves as an important information "matchmaker" that links indigenous knowledge, local observations and geophysical or biological studies and insights. In fall of 2012 and 2013 this role has been explored further by developing a standardized protocol for observations of potentially hazardous interactions of ice, water and weather during fall freeze-up in a collaboration between LEO and SIZONet. This protocol was available to all LEO partners and allowed for intercomparable reports firmly grounded in traditional knowledge from communities impacted by ice hazards during freeze-up. Such approaches are being further explored and present a viable approach in building an interface between indigenous sea-ice expertise and information needs relevant, e.g., in the context of hazard mitigation and emergency response (Eicken et al., 2011).

The Sea Ice for Walrus Outlook (SIWO) is a cooperative project that takes this approach of knowledge exchange about the ice environment one step further. In a collaboration between the National Weather Service, the Eskimo Walrus Commission, Yupik and

Inupiaq sea-ice experts, UAF and the Arctic Research Consortium of the U.S. (ARCUS), improved weather and ice forecasts, satellite data and community-based observations of ice conditions are shared on a weekly basis to improve safety of hunters and other community members out on the ice or the water (www.arcus.org/search-program/siwo). In the context of ice and weather forecasts, local observations and traditional knowledge can provide important feedback on the accuracy of model output in regions with complex ice circulation, strong currents not captured by simulations and ice distribution patterns not fully detectable through remote sensing.

Along similar lines, studies by Huntington et al. (2013); Robards et al. (2013) and Kapsch et al. (2010) have explored how traditional knowledge of ice conditions relevant for subsistence hunting activities in the Bering Sea relate to coarser-scale information about the ice environment captured through remote sensing and climatological data.

In the context of this report, several points are worth noting with respect to emerging approaches and technologies relevant in capturing and sharing traditional and local knowledge. First, digital technology can greatly enhance the access as well as the extraction of specific information content from TLK. This ranges from development of dedicated databases that take strong guidance from indigenous experts and communities on database design, access and other relevant constraints (see Eicken et al., 2014) to digitization and transcription of recordings of elder and expert knowledge. Project Jukebox at UAF's Oral History program is in the process of making recordings dating back to the 1970s available in this fashion. Part of this record are the interviews conducted by Shapiro, Toovak and others of North Slope elders and sea-ice experts in the 1970s. This work was meant to evaluate the circumstances and frequency of occurrence of very rare but potentially catastrophic ice-push events (Iñupiaq: ivu) in the context of coastal oil and gas infrastructure (Shapiro et al., 1979). We are not aware of other studies of this breadth and depth, but in light of planned development in Alaska coastal waters there is an urgent need to capture sea-ice knowledge of the current generation of elders. This is particularly relevant as the Beaufort and Chukchi Seas with heavy ice drifting in from the High Canadian Arctic and substantial interannual variability will likely continue to experience occasional extreme ice years for some time to come, even as overall summer ice extent is reduced arctic-wide.

Most recently, experts' workshops that bring together indigenous ice experts and hunters, university researchers, agency personnel and ice experts from industry have proven very helpful in taking stock of available information about ice development and dynamics in a common reference framework. A report by Johnson et al. (2014) illustrates the range of pertinent information emerging from workshops held in Barrow and Wainwright in 2013, in particular as relevant to hazard mitigation and emergency response. Further refinement and regional expansion of this approach may yield important baseline information for a broad stretch of coast impacted by sea ice processes.

In working with holders of traditional and local knowledge, it needs to be recognized that we are currently lacking effective programs or frameworks that help support sustained

community-based observations. Research projects such as BSSN or SIZONet cannot take the place of operational programs. Neither are networks such as LEO set up to address the information needs centering around the ice environment. In fact, one of the few operational programs that may serve as a model, the National Weather Service's cooperative observer program continues to be under threat, despite its demonstrated value in Alaska where meteorological observations are scarce and far between.

North Slope Borough/Shell Baseline Studies Research

In light of increased industrial activities in United States Arctic offshore waters, effective response to spills of oil and hazardous substances in coastal, seasonally ice-covered waters is universally recognized as a critical challenge to sustainable development in northern Alaska. Due to limited in-situ and remote sensing observations, current and ice motion patterns in coastal settings are poorly understood. To address this shortcoming, workshops held in March 2013 in Barrow and Wainwright, Alaska, focused on nearshore ice and ocean currents of the coastal Chukchi and Beaufort Seas. Indigenous experts from Barrow, Wainwright, Point Lay, and Nuiqsut met with scientists from the University of Alaska Fairbanks and other institutions to discuss ice conditions and ocean circulation and to identify the knowledge critical to emergency preparedness and response.

This report informs agencies about coastal Chukchi and Beaufort Sea ice and ocean circulation, seasonal freezing, ocean access, and local expertise. Workshop recommendations call for measurements in new places and at specific times of year to improve our understanding of nearshore ice and ocean current variability and seasonality.

Local and indigenous experts described ice and ocean features, often using Iñupiaq terms. Whalers and hunters learn from elders and by experience under conditions critical to success and survival. Local knowledge at the scale related to hunting and travel experience is rich in detail and complements the typically larger scales of remote sensing and ice-ocean models.

The wealth of sea ice experience from whaling and hunting on the ocean shared at this workshop clearly demonstrates how local and indigenous knowledge (LIK) can inform and guide sea ice and ocean circulation research and design. Such practical knowledge improves safety and provides the foundation for efficient fieldwork.

Communication issues and different frames of reference arose as a broad range of experts described what they know. Workshop challenges were partially overcome and highlight the beginning of truly shared knowledge established at this workshop. We hope this process continues to advance ice and ocean research particularly in the context of safety and emergency preparedness.

The majority of participants acknowledged that important progress was made toward establishing meaningful contacts and relationships, which may provide a foundation toward enhancing communication between agencies, response professionals, and local experts in the event of an emergency.

Local experts experienced in navigating the ocean and maneuvering in sea ice 1) described weather, ice, and ocean currents, 2) located convergence zones offshore where birds and animals congregate for feeding or resting, 3) identified places where flotsam washes ashore, 4) shared navigational limits imposed by slush ice formation, lagoon freeze-up, and shoreline freezing, and 5) discussed recently observed environmental change.

The workshops confirmed that local input and partnerships are essential to emergency response planning. There was concern that logistics and infrastructure in coastal communities would be overwhelmed during an emergency or spill response. Participants called for distributed material that aids emergency and oil spill responders to be readable and well documented, first-contact lists to be readily accessible, and known ocean access points and potential staging areas to be described clearly and marked on charts.

Our research recommendations are the result of communication among experts. New research should address knowledge gaps, improve our conceptual model of ice and ocean seasonality, and lead to a better understanding of processes that limit seasonal access to the ocean.[11]

[11] http://www.iarc.uaf.edu/sites/default/files/node/4399/currentsiceknowledgewsreport2014s_pdf_36165.pdf

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