Innovative Technology Development for Arctic Exploration

J. N. Cross
Cooperative Institute for Alaska Research
University of Alaska, Fairbanks, and
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, WA, USA
Jessica.Cross@NOAA.gov

C. W. Mordy and H. M. Tabisola
Joint Institute for the Study of Atmosphere and Ocean
University of Washington, and
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, WA, USA
Calvin.W.Mordy@NOAA.gov
Heather.Tabisola@NOAA.gov

C. Meinig, E. D. Cokelet, and P. J. Stabeno
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, WA, USA
Christian.Meinig@NOAA.gov; Edward.D.Cokelet@NOAA.gov; Phyllis.Stabeno@NOAA.gov

***Abstract*— The US Arctic and sub-Arctic regions are rapidly changing, creating potentially large impacts to marine ecosystems and ecosystem services. However, much of the current observing technology is ill suited to fully quantify these dynamic changes. The harsh, remote environment, expansive area, and extremely fine scale features present clear barriers to the efficient collection of effective environmental intelligence. In order to meet these challenges, NOAA's Pacific Marine Environmental Laboratory, with support from Ocean and Atmospheric Research Division, has created the Innovative Technology for Arctic Exploration (ITAE) program to facilitate the development of new autonomous platforms and high-resolution sensing technologies that may be able to address this critical gap in mission capabilities. During the program's primary field testing year, ITAE successfully completed two large-scale research missions in the Bering and Chukchi Seas involving multiple new Arctic-capable platforms, including the Saildrone unmanned autonomous surface vehicle (Saildrone, Inc.), the Profiling Crawler (PRAWLER; NOAA-PMEL), a moored instrument drastically improving vertical resolution of data collection; and the Expendable Ice Tracking (EXIT) Floats, which allow for under-ice data collection (NOAA-PMEL). Through these platforms, ITAE also tested a variety of novel sensing technologies, such as the recently developed microfluidic nitrate sensor, the Lab-on-a-Chip (National Oceanography Centre, University of Southampton). Together, these developments helped to assess important and previously inaccessible aspects of the sea ice melt season. However, important technical challenges remain, including autonomous ecosystem assessment tools that could effectively monitor and aid management of the region's multi-billion dollar annual commercial and subsistence fishing industries.**

Keywords—Arctic; climate change; sea ice; ecosystem monitoring; Technology development; Unmanned Autonomous Vehicles (AUVs); High-resolution sensors; Saildrone; PRAWLER; ITAE

I. Introduction

The US Arctic, comprising the Bering, Chukchi, and Beaufort Seas, is home to one of the world most highly productive ecosystems. Alaskan fisheries make up more than half of the total commercial fish catch for all US waters, comprising a multi-billion dollar annual industry. The region is also an important cultural resource for indigenous communities, where roughly 95% of households participate in subsistence fishing. However, these systems are currently in the midst of rapid environmental changes [1, 2].

Arctic change has been rapid and extensive over the last several decades, especially in comparison to low–latitude areas. Since the 1980s, sea-ice thickness, persistence, and coverage have declined dramatically in response to a warming climate, with overall sea-ice volume losses averaging ~3000 km^3 each decade [3]. Changes in sea ice dynamics and warming affect a broad spectrum of the Arctic system, including ocean physics, chemistry, and food webs [1-2, 4-8], and are reflected more widely in the weather patterns at low latitudes [9-15]. The current trends are expected to continue in the future, intensifying the impacts of Arctic change on the United States and other parts of the globe [11].

These rapid changes are bringing the Arctic to the forefront of US security and stewardship interests. In 2013, the White House released the US National Strategy for the Arctic Region [16]. The National Strategy emphasizes the need to advance national security; responsibly manage resources; protect the environment; and support indigenous communities, using the best available scientific information. The National Oceanic and Atmospheric Administration (NOAA) and its partners support these decision making processes by acting as the US environmental intelligence agency, transforming shared international data, analysis, modeling, and assessment into

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actionable information for responsible Arctic resource management [17].

While scientific understanding of the Arctic region is advancing rapidly, much of our current technological capabilities are ill-suited to observing these dynamic changes. The harsh, remote environment, expansive area, and extremely fine scales of change represent clear barriers to cost-effective, efficient collection of data through solely remote sensing and traditional field approaches (e.g., aircraft, ships, and moorings). Autonomous vehicles have the potential to fill these gaps, as identified by many other programs [18-22]. However, some of these platforms require additional development to withstand the extreme conditions of the Arctic environment.

In order to meet these challenges, the NOAA Office of Oceanic and Atmospheric Research (OAR) has provided support to the Pacific Marine Environmental Laboratory (PMEL) to create the Innovative Technology for Arctic Exploration (ITAE) Program. The program mission is to facilitate development of new, Arctic-capable autonomous platforms and high-resolution sensing technologies to expand NOAA's current operational capabilities.

Here, we describe the current activities of the ITAE Program. First, we discuss current changes occurring in the Arctic, and why autonomous platforms and high-resolution data collection are ideally suited to measuring and monitoring these changes. Next, we highlight the current lines of effort of the ITAE program, including the two successful large-scale field missions of our inaugural field year, as well as the laboratory testing of multiple novel sensors and platforms. Lastly, we describe continuing research and development, and the new ways the ITAE program continues to explore innovative technologies for Arctic research.

II. Key Elements of Arctic Change

Changes in sea ice are the most visible manifestations of climate change in the Arctic. Clear decreases in sea-ice extent, concentration, thickness and volume are shown in the satellite record [23-27]. Sea ice also serves as a sensitive indicator of climate dynamics in the area as a whole [28]. Sea ice and glacial melt increase fresh water inputs to the Arctic Ocean [29-34], influencing circulation patterns and ocean heat cycling. Greater open water area allows for greater heat exchange with the atmosphere. Together, changes in ocean circulation and heat inventories cause broad changes to weather patterns extending well beyond the Arctic region [35-36].

The Arctic carbon system is also rapidly changing [37]. Like ocean heat, increased open water area allows for greater exchange of CO_2 between the atmosphere and upper ocean, contributing to accelerating rates of ocean acidification and decreases in ocean pH [38]. This process is exacerbated by increasing concentrations of sea ice and permafrost melt and river waters, which are naturally low in pH compared to the surface ocean [30, 39]. Warming ocean temperatures also destabilize marine gas hydrates, potentially increasing ocean acidification and oxygen depletion in the marine environment [40]. Greater open water area and increased storminess are also contributing to enhanced upwelling events, which bring can bring low pH waters to the ocean surface [41].

Ocean warming and decreases in pH can have large, cascading impacts Arctic food webs [42], potentially impacting human ecosystem services. At the base of the ecological system, the timing and location of phytoplankton production and respiration are tightly linked to the seasonal sea-ice cycle [43-46]. Changes in phytoplankton production also impact the energy pathway to benthic biological systems and sediments as well as higher trophic levels, including fish, seabirds, seals, walrus, and whales [42].

The US Arctic supports some of the largest commercial and subsistence fisheries in the world. Warming, sea-ice losses, and changes in the carbon system may reduce recruitment of juvenile walleye Pollock (*Theragra chalcogramma*) by midcentury [47]; restructure the populations and productivity of benthic ecosystems [42] and reduce growth and survival of king and tanner crabs (*Paralithodes camtschaticus* and *Chionoecetes bairdi*, respectively) [48]; impact seabird populations [43, 49]; reduce viable habitat for ceteceans, pinnipeds, and polar bear populations [5, 50, 51]; and dramatically increase economic and social risks for coastal communities in rural southeast and southwest Alaska [2] and potentially in lower latitude areas [52].

III. Development of New Technologies

Given these key elements of Arctic change, it will be critical to monitor changing heat, salt, and carbon fluxes as well as ecosystem variables in order to effectively manage Arctic Ocean resources. A critical challenge to this mission is that this area is both vast and complex, necessitating data collection at small scales over very large areas [e.g., 53]. The coastline of the state of Alaska alone is more than 10,000 km—more than the combined length of the East, West, and Gulf coasts of the continental US [54].

These scientific needs make it clear that the ideal platforms and sensors for studying Arctic change should be able to withstand multiple long deployments that cover large areas and collect high-resolution data. Some current tools can selectively meet these needs; for example, remote sensing techniques like satellite observations can collect data over extremely large areas and at high resolution for some surface variables, although weather patterns and highly turbid coastal areas can be challenging [55-58]. From another perspective, traditional ship-based observations can collect extremely diverse data at high resolution from expansive areas, but high costs limit the overall duration and frequency of these missions [56, 59].

According to these criteria, autonomous moorings, gliders and drones, as well as new sensors that detect small changes and collect data at rapid intervals may fill this important niche, especially as payload, power, and sensor capacity increase [18-22, 58-60]. However, many of the currently available and new platforms and sensors are designed for conditions more typical of the tropics, where temperatures are warm, platform accessibility is simple, and mechanical hazards like sea ice and biofouling typical of highly productive sub-polar systems are fewer.

The ITAE Program works under a tiered development system, where we integrate novel sensing technologies with innovative platforms in late-stage development; adapt existing technologies for use in the expansive, harsh, and remote Arctic environment; and engage in longer-term development initiatives designed to address underserved technological needs. The central goal is to efficiently develop and transfer this technology for use in a broad array of conditions and a variety of purposes by the wider community.

During 2015, the program successfully completed two large-scale field missions, including a three-month Bering Sea deployment of two Saildrones, novel wind- and solar-powered unmanned surface vehicles, and a two-month, multi-platform integrative project in the Chukchi Sea. We also investigated several new sensors for their suitability in the Arctic environment and use on autonomous platforms, including the carbon PRAWLER (Profiling Crawler), an autonomous crawling carbon instrument for moored systems; the Lab-on-a-Chip (LOC), a nitrate sensor from the class of recently developed fluidic chemical analysis microplates; a Simrad Wide-Band Acoustic Transceiver (WBAT), a new-generation echosounder for moored and mobile autonomous platforms; and the novel Expendable Ice Tracking (EXIT) Floats for under-ice sampling.

A. 2015 Field Program: Bering Sea Surface Mapping

During 2015, NOAA OAR Laboratories and the ITAE program worked with Saildrone, Inc. under a Cooperative Research and Development agreement to develop the Saildrone platform for high-latitude research purposes. The primary

Fig. 1. Saildrone SD-128 during the 2015 Bering Sea Surface Mapping mission. Photo by Mark Frydrych, NOAA NMFS/AFSC.

Fig. 2. SD-128 Track through Bering Sea during the 2015 Surface Mapping Mission.

advantage of the Saildrone is its speed, endurance, and maneuverability, which allow launch and recovery from shore and enable extended research missions, an important capability gap in current unmanned surface vehicles and a critical mission capability for Arctic research and monitoring.

This collaboration resulted in several important modifications of the Saildrone platform and the associated sensors [61]. One of the key variables for a high-latitude mission in the Pacific Arctic was mitigation of potential biofouling, given the region's high rates of primary production. While some sensors can be purchased with wipers, copper mesh, or other biofouling deterrents, a particular concern for the north Pacific is gelatinous zooplankton and cnidarian biomass [62-66]. Some modifications to the central Saildrone sampling intake were made in order to deter clogging [61]. Another concern was power generation, as solar energy can be problematic in areas where daylight hours are limited and weather patterns limit direct sunlight.

Two Saildrones with basic sensor payloads were deployed in the Bering Sea in mid-April and recovered 97 days later in late July [Fig. 1, 2]. During this time, the Saildrones collected approximately 2 million samples per day. One- and 10-minute averaged data was telemetered to shore to allow for responsive sampling, with higher-frequency data stored on board. Owing to the platform's speed and maneuverability, we tracked two important fine-scale features, including a sea-ice melt signature as well as the edge of a river plume [61, 67]. Overall, the Saildrones each covered a remarkable 7800 km [Fig. 2].

B. 2015 Field Program: Multiplatform Research in the Chukchi Sea

Due to the remote and harsh environment of the Arctic, research activities in this region are greatly enhanced through collaborative efforts and partnerships that leverage complementary capabilities and resources. In 2015, the ITAE

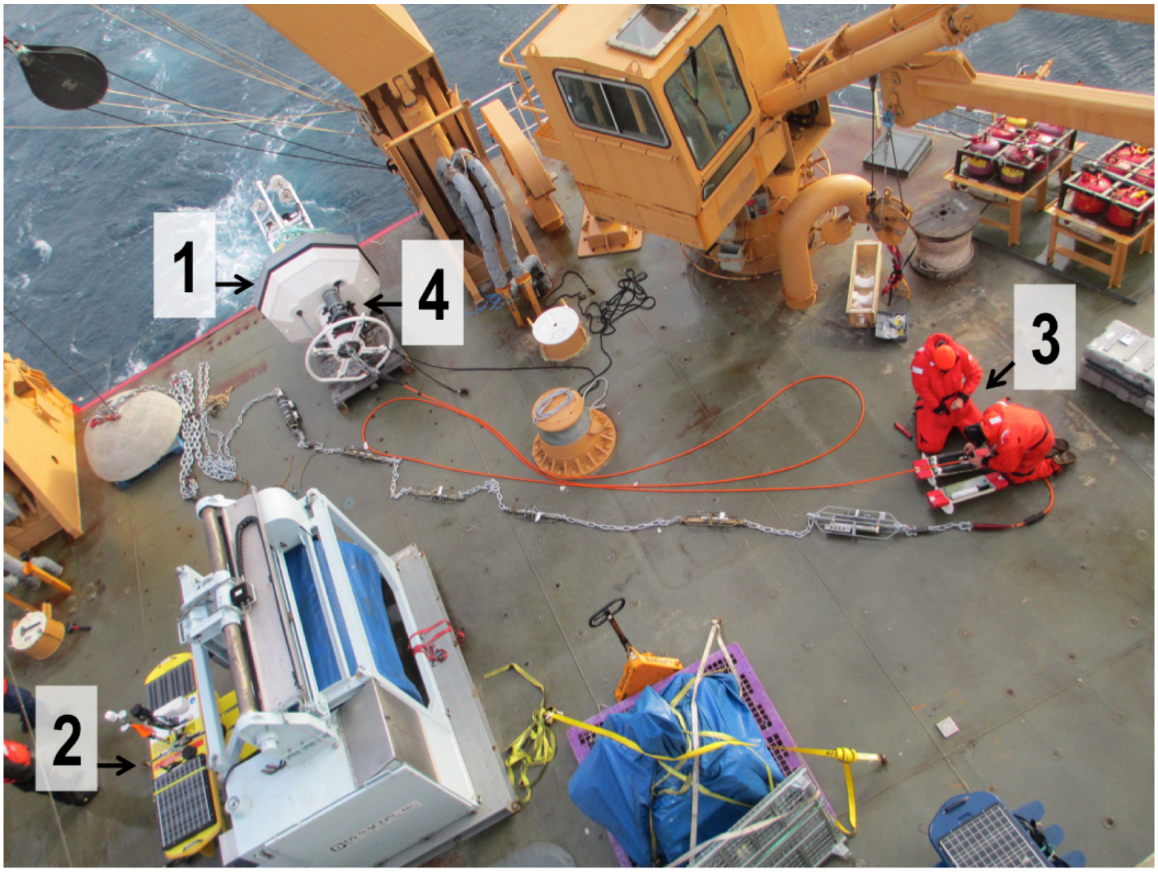

Fig. 3. Four of the ITAE technologies used during the multiplatform Chukchi Sea research mission being prepared for deployment via the US Coast Guard Cutter *Healy*. (1) Radiometer buoy. (2) Wave glider. (3) Profiling Crawler (PRAWLER). (4) Lab-on-a-chip (LOC) microfluidic nitrate sensor. Photo by Ryan Fitzler, National Geo-spatial Intelligence Agency (NGA).

program partnered with the NOAA's Office of Ocean Exploration and Research and the US Coast Guard (USCG) to deploy a radiation mooring and two Wave Gliders in the Chukchi Sea [Fig. 3]. Integrating the data from these two unique platforms allowed for the assessment of physical, chemical, and biologically important variables in the technically challenging seasonal ice zone.

As part of this project, ITAE deployed a variety of new instrumentation on a moored platform, including the carbon Profiling Crawler (PRAWLER) [68] [Fig. 3]. The PRAWLER uses surface wave energy to power a profiling instrumentation package along a mooring line, allowing for the collection of profile data over long deployments, and has control of sampling frequency in time and depth. The PRAWLER builds on a continuing development effort at PMEL to reduce the cost and complexity of moored platforms and increase vertical sampling resolution.

ITAE also collaborated with the National Oceanography Centre at the University of Southampton to test the Lab-On-A-Chip (LOC), a new, smaller (12 cm x 10 cm) microplate nitrate sensor which conducts *in-situ* nutrient chemistry with on-board reagents and standards [69] [Fig. 3]. At present, microplate-sensors like the LOC are revolutionizing the collection of ocean chemical data by providing *in-situ* standards for data calibration and monitoring of sensor drift. However, the LOC is still in its early development phases, and operates at a relatively low sampling frequency. By combining the LOC with commercially available, uncalibrated high-resolution sensors, ITAE generated a high-resolution, calibrated nutrient data stream.

In addition to the radiation buoy, surface data was collected from two autonomous, robotic surface vessels, the PMEL Carbon Wave Glider and Ecosystem Wave Glider [Liquid Robotics] [Fig. 3]. The surface data collected by these instruments over a broader area will provide important insights into the evolution of the upper water column after ice retreat, including changes in heat and carbon fluxes that result from freshwater stratification [70].

An exciting innovation deployed during this project were the PMEL Expendable Ice Tracking (EXIT) Floats, a new conceptual design for under-ice data collection [Fig. 4]. EXIT floats are initially anchored to the ocean bottom, and a timed release allows the instrumented floats to surface under the ice. The float tracks important physical and biological variables during the ascent through the water column and under the ice matrix until it encounters open water conditions and transmits data. Data transmission in the marginal sea-ice zone continues through the end of the sensor's battery life. One challenge to this design is the mechanical hazards of unstable ice, such as potential crushing between rafting floes. Two prototypes were

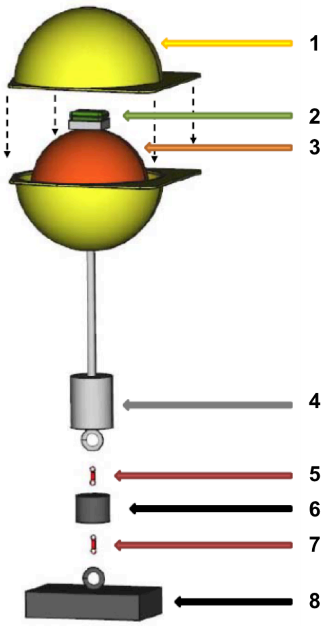

Fig. 4. Schematic of the Expendable Ice Tracking (EXIT) Float as developed by the researchers at the Pacific Marine Environmental Laboratory (PMEL). (1) 'Hard hat' casing. (2) Satellite tag. (3) Trawl float. (4) Counter-weight. (5) Secondary Release. (6) Weight. (7) Primary Release. (8) Anchor.

deployed during this mission, one of which is now transmitting data. The broader vision is the deployment of a suite of floats that will be released periodically throughout the ice melt process.

Together, these technologies will be able to provide information about the biophysical impacts of sea-ice melt on the Chukchi Sea ecosystem by monitoring the evolution of key physical, chemical, and biological variables of the upper water column beginning during ice retreat and through the summer. Data collection and analysis are ongoing at the time of this writing.

IV. Continuing Innovation

The central goal of the ITAE program is to develop new platforms and sensing technologies that fill gaps in current operational capabilities. The two missions described above were designed to deploy highly developed technologies in the first tier of operational readiness. In the next stage, ITAE is working with other sensors and platforms in earlier stages of development.

Through a collaboration with NOAA's National Marine Fisheries Service, ITAE is working to develop the mooring-based Simrad WBAT echosounder for deployment on the Saildrone, and will be conducting a test mission in the coming year. This research prototype could represent an important new capability for annual fishing surveys. This technology could provide unprecedented reconnaissance data that could better guide ship-based teams to more efficient survey formats, as well as extend the spatial and temporal coverage of the core surveys. Additional capabilities being designed for the Saildrone include a methane / CO_2 analytical system for ocean acidification surveys in the Arctic.

There are also important gaps in the current capabilities of autonomous vehicles that will require focused, long-term development. For example, unstable ice floes represent extreme risks for autonomous vehicles; historically, this has limited studies of the process of ice melt and under-ice dynamics. In addition to the mechanical hazards of sea ice, under-ice navigation represents an enormous challenge for vehicles usually directed by satellite communication.

ITAE has made a preliminary investigation into this problem by investigating the principle and effectiveness behind the EXIT Float, and many programs and organizations are pursuing these problems from a variety of perspectives. For example, the Marginal Ice Zone project, led by the Office of Naval Research and the University of Washington Applied Physics Laboratory, used acoustic point sources deployed in the sea ice to guide under-ice glider arrays [71]. Ice-capable surface and sub-surface vehicles will be an important breakthrough for the Arctic research community in the coming years.

Building a better understanding of climate change impacts on Arctic ecosystems will continue to be a challenging and expensive undertaking, especially through these early phases of research and development. However, some of this effort can be offset by the strong precedent for collaboration and partnership so typical of the Arctic research community. For example, international collaboration between Arctic states is facilitated by the Arctic Council, an international forum for sustainable development, the environment, and scientific collaboration. Internally, the US supports Arctic research through all of the major federal scientific agencies, and coordinates their activities through the Interagency Arctic Research Policy Committee.

One notable recent program that has emerged as a result of this cooperative research environment is the Distributed Biological Observatory (DBO), a collection of sites prioritized by multiple funding agencies for frequent opportunistic occupation, including NOAA, the Bureau of Ocean and Energy Management, the International Arctic Science Committee, and the National Ocean Council [72].

During the first two years of this program, ITAE has formed strong partnerships with researchers at several universities, engineering firms, and local communities, and continues to reach out in new directions with the Alaska Sea Grant, the NOAA Fisheries Observer Program, and Pew Trusts. This tradition of multilateral integration will be critical to the program's success.

NOAA emphasizes data synthesis and cross-line office communication is also integral to Arctic research and the formation of actionable environmental intelligence. The ITAE program will transition these newly developed Arctic research technologies to the rest of the community, in order to begin the collection of data that can support foundational scientific understanding and predictive capacities for Arctic environmental change, and its impacts on US communities and economies.

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