Title: Ocean and ice observations from submarines in the Arctic

A Community White Paper for the Arctic Observing Summit 2013

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Summary

Submarines have provided some of the longest observational time series in the Arctic Ocean that include measurements taken in a consistent and comparable manner for ice thickness, water temperature and other critical properties. While these platforms are not operated within the planning environment of civilian science, their unmatched mobility and capabilities for a variety of sampling modes and sensors makes them an important asset for recording the environmental status and changes within the Arctic. The SCIence EXercise (SCICEX) program was created with U.S. Navy (USN), federal agency and civilian participation to optimize the extent and coordination of scientific information obtained from U.S. submarines in the Arctic. A recent Science Plan lays out the scientific priorities for the program and emphasizes its role in the Arctic Observation Network. Although the USN envisions a continued presence in the Arctic, the effective integration of submarine observations with the growing amount of surface ship, mooring and drifter data presents an ongoing organizational challenge. Improvements are planned in several aspects of data and sample collection from submarines to enhance the importance of their missions in the Arctic Ocean to assess the reduction in ice cover, the identification of water masses, the sampling of biological populations and the measurement of ocean bathymetry.

1 Introduction

Nuclear powered submarines have proven to be extremely capable in collecting observations of environmental conditions in the Arctic Ocean, and have amassed a variety of important scientific information in all deep-water regions. Some of the highlights of these scientific results are included as an Appendix to this report for the interested reader. The report itself focuses on the role the submarine can play as part of the Arctic Observing Network (AON; IARPC, 2007) in terms of its strengths and limitations both as an observational platform as well as a platform whose primary mission is not scientific. Additional coverage is provided on the specific plans for future submarine sampling in the Arctic for the purposes of AON planning as well as the planning of individual researchers. In addition to seeking future opportunities to collect data, this involves the transfer of data collected in the Arctic from these platforms to the public domain for scientific use through the extraordinary cooperation of the U.S. Navy (USN) and the British Royal Navy (RN) with the civilian, academic community. In the U.S., this cooperation was formalized by the creation of the SCience ICe EXercise (SCICEX) program, a joint military – academic program that has been managing academic scientific observations from U.S. submarines since 1994.

Scientific observations with both the USN and RN began well before this time however. Comprehensive summaries of submarine cruises prior to 2001 can be found in Rothrock et al. (1999a) and Edwards and Coakley (2003) and at the SCICEX web site supported by the National Snow and Ice Data Center (NSIDC): http://nsidc.org/scicex/index.html.

A range of budgetary and political factors determines the level of this military-civilian cooperation in the Arctic that is largely beyond the scope of this overview. The USN formally recognized the strategic challenge of climate change in the Arctic in their last Quadrennial Defense Review however, and created a Task Force Climate Change (TFCC) to oversee the recommended Navy actions. These and other initiatives indicate that the USN intends to expand its activity in the Arctic, which may provide more opportunities to collect SCICEX data as well as more opportunities for collaboration outside of SCICEX. The relevant action items developed by the TFCC with respect to future science observations in the Arctic are detailed in a later section of this report.

Figure 1. Schematic diagram of a modern nuclear powered submarine based on the retired U.S. Sturgeon (SS637) class.

The use of manned submarines for arctic exploration began in 1931 with the cruise of the re-fitted World War I submarine O-12 (re-named the Nautilus; The papers of Lincoln Ellsworth, 1913-1952). The expedition included oceanographers such as Harald Sverdrup but produced few scientific observations due to significant technical problems. The USN overcame operational limitations regarding submarine work in the Arctic two decades later with the development of nuclear-powered submarines. This technological advance led to the first crossing beneath the arctic ice pack in 1958 by the USS Nautilus and the first through-ice surfacing that same year. These and subsequent arctic crossings have included scientific participation from what is now known as the Navy Arctic Submarine Laboratory (ASL) in order to gain scientific knowledge in support of Arctic submarine operations and to guide the submarines in the ice. Navy research has focused on a variety of topics relevant to submarines in the Arctic including ice strength and properties, ice formation on ship components and especially under-ice sonar (Leary, 1999). Over the last several decades, military submarines have provided useful scientific information in every major oceanographic discipline including sea ice, marine geophysics, and ocean physical, chemical and biological properties. The relevant parts of a modern, nuclear-powered submarine are shown in Figure 1. All submarine depths refer to the keel depth that is a number of meters below the sail where most of the autonomous, underway-sampling devices are located. In addition to these autonomous instruments, it is possible to launch external sensors such as eXpendable Conductivity – Temperature and Depth (XCTD) probes and collect discrete water samples while the submarine is submerged. More details on each of these sampling modes will be discussed as relevant in subsequent parts of this report.

2 Evolution of submarine scientific use in the Arctic

An important determinant of the scope of scientific measurements shared between the USN and civilian scientists is the Memorandum of Agreement (MOA) in effect with the USN. Two have defined scientific data sharing from U.S. submarines over the last two decades. In 1994 an inter-agency MOA was signed among the Navy, NSF, NOAA and the USGS that initiated what has come to be referred to as SCICEX Phase I. This MOA, along with the unique availability of the 637 class submarines before their retirement, led to a series of dedicated science missions to the Arctic in 1993 and 1995-1999. Civilian scientists participated directly in the planning and execution of these missions through the Navy's Arctic Submarine Laboratory (ASL). Phase I ended with the reduction in the submarine force. SCICEX Phase II was developed under a new MOA in 2000 among the USN, ONR and NSF. This MOA set up three functioning bodies to oversee Phase II activities: 1) An operational planning board composed of ASL and the USN; 2) An Interagency Committee (IAC) that includes representatives of each of the participating agencies and the Arctic Research Commission; and 3) The Science Advisory Committee (SAC) that includes representatives of each of the participating agencies and 6 non-permanent members from the academic community. The SAC developed a science plan to guide future SCICEX activities (SCICEX Science Advisory Committee. 2010).

As presently configured, the SCICEX program is organized around Science Accommodation Missions (SAMs) that do not carry civilian scientists other than those from ASL and are designed to have limited or no impact on the submarine's primary military mission. Although less scientific information can be obtained from SAMs than from dedicated missions, past submarine data collection opportunities have shown that all military arctic missions have scientific value, as they include, for example, routine measurements of ice draft, bottom profiling and underway salinity – temperature and depth (CTD) and other hull mounted sensors. These data have contributed significantly to the historical record of oceanographic and climatological observations in the Arctic. Recognizing the value of data from these routine missions, more detail on the plans and management of future SAMs are discussed later in this report.

Figure 2. Map of the Arctic showing several relevant features. The yellow line indicates the extent of the SCICEX data release region. The solid and dashed white lines show the extent of the sea ice in September of 2001 and 2007 respectively. The 5 numbered and shaded regions denote the priority sampling regions for future U.S. submarine crossings in the Arctic.

3 Future implementation and goals for submarine observations

Recent efforts to extend and improve the scientific – military collaboration in the Arctic have taken place in both the U.S. and Britain. In addition to the plans put forth by the SCICEX Phase II Science Plan (SCICEX Science Advisory Committee. 2010), relevant parties assembled in a similar planning exercise in the U.K. (Boyd, 2010). The RN has not made specific plans public for their future work in the Arctic however and only the results of the SCICEX planning are covered here. SCICEX Phase II planning attempted to integrate the sampling priorities of each of the sub-disciplines (sea- ice, hydrography, chemistry, biology and bathymetry) together with the anticipated submarine operations in the Arctic to propose the 5 sampling corridors depicted in Figure 2. Not shown in Figure 2 is the direct transit between the Atlantic and Pacific Oceans that is used routinely for submarine crossings and from which a significant amount of data have been collected. The new sampling corridors in Figure 2 represent an attempt to traverse under-sampled and/ or critical regions for each of the sub-disciplines. For example, corridor 1 provides bathymetric data near the Lincoln Sea and corridors 2 and 5 sample regions that are newly ice-free summer. Corridor 3 is used for submarines taking part in the periodic ICe EXercise (ICEX) camps, another possible source of scientific information for SCICEX. Particular emphasis was placed on regions of extensive historical data for ice draft measurements such as the North Pole region of corridors 1 and 4. Additional recommendations were made on the prioritization of seasonal sampling for each of the sub-disciplines.

An attempt was also made in the planning process to provide guidance on how to utilize any additional sampling time that may become available beyond that provided by a direct transit. A series of increasingly more ambitious sampling plans was developed in half-day increments to guide cruise planners on how to best utilize from 0.5 to 3 additional days of sample time. This process produced a guidance matrix for cruise planning and the expanded disciplinary sampling that could be done with each increment of additional time. In practice, when submarines are scheduled for Arctic operations, ASL will examine each mission for its potential to collect SCICEX data. In doing so, they will consider the following:

- Type/destination of the transit
- Priorities laid out in the Science Plan, Part 1
- Suitability of the submarine's equipment for data collection
- Amount of time that might be added to the transit to perform data collection
- Time of year
- Complementary plans of other elements within AON
- Sampling conducted on recent previous SAM cruises
- Feasibility and cost-effectiveness of installing extra scientific equipment on board the submarine

The actual scientific observations will be supervised and carried out by the ASL in consultation with participating civilian scientists before the cruise. Operating procedures for each of the standard sampling activities are being developed to identify hazardous materials, equipment needed and handling procedures to facilitate a rapid response to a SAM opportunity. Two classes of submarine are currently the most important in terms of Arctic crossings: the 688i and Virginia class. The specific equipment available will vary depending on the submarine class conducting the operations, but will generally include:

- Conductivity, temperature, depth (CTD) profiles taken by expendable probes
- CTD and other sensor data taken from hull mounted systems
- Bathymetry recorded by installed fathometers/ bottom sounders
- Ice profile data from upward-looking sonar/ topsounders
- Water samples for salinity calibration and other shore-based analyses
- Supporting navigation from the submarine's inertial navigation system, and operational data at a non-classified level

4 Sampling issues and pending improvements

Priorities for future improvements in submarine sampling include several issues identified in prior SCICEX missions. Some of these issues are already being addressed as part of on-going research. For example, the precision of the upward looking sonar (ULS; topsounder) data has averaged 22 cm over the entire submarine data set

(Wesnahan and Rothrock, 2007; Rothrock and Wensahan, 2007). This should improve with newer, digital versions of the ULS that are available. Also, the success rate of the submarine launched XCTD (U/ISSXCTD) probes has been disappointing. Problems include non-working probes and probes that fail to collect data throughout their design depth range. The data successfully returned have been accurate however (Figure 3). Improvements are also underway for the collection of discrete samples. This includes the development of better portable equipment and freezer space for SCICEX samples. The submarine can sample a depth profile either by transitioning between a series of 'stair-steps' in depth as it transits, or by spiraling up from depth at one location. The precision of the sample depth is an additional concern for the discrete samples however. Ideally, flow across the submarine's hull is laminar and the depth of origin for a water parcel can be traced to its initial interaction with the leading edge of the hull. Drift angles or turns generate side forces and vortexes however, that complicate the prediction of surface flow across the hull (Watt, 2005). The sampling depth for the through-the-hull samples therefore is approximate to perhaps several meters but certainly not worse than that of a standard Niskin cast from a rolling surface ship.

Figure 3. Comparison between standard CTD casts from APLIS ice camp and co-located U/ISSXCTD probes in 2011.

Improvements that require engineering changes to the submarine, can only be done through a formal engineering process of Temporary Alterations (TEMPALTS) to accommodate specific modifications. Work is underway in this regard to streamline on-board data collection by developing a scientific data system separate from the military system. Some level of alterations also will be needed for more extensive hull mounted sensors to detect chemical and biological properties such as oxygen, pH, Chl-*a* and DOC that would greatly increase the information collected autonomously along track.

5 Data Release Procedures

Raw data or samples collected from U.S. submarines in the Arctic are normally designated as "classified" by the Navy and are archived at ASL. A de-classification process follows to identify the data that meet the spatial and operational criteria for release. For U.S. submarines, data for release must be collected within the SCICEX Data Release Area, defined to be outside of other nations Exclusive Economic Zones (EEZs). This results in a region that is roughly half of the Arctic Ocean and includes almost all of the deep basins (Figure 2). Data can only be released from times when the submarine is travelling less than 25 knots (12.86 m/s) and above 244 m depth. While the release area and depth restrictions limit submarines mainly to surface waters of deep basins, sensors and expendable probes can extend sampling to a much greater part of the water column. In the declassification process, data from appropriate arctic submarine missions are reviewed and filtered according to the established restrictions by ASL before being publicly released. For most missions, this declassification process occurs within 4-6 weeks of the cruise. In accordance with the SCICEX Phase II MOA, all data from SCICEX SAMs will be publically accessible through the National Snow and Ice Data Center (NSIDC; http://nsidc.org/scicex/index.html) as soon as it becomes available. The SCICEX SAC, in coordination with the SCICEX Interagency Committee, will inform the scientific community of the release of declassified SCICEX SAM data to the NSIDC through the best available medium (e.g., ArcticInfo information server operated by the Untied States Arctic Research Consortium of the United States).

6 The role of submarines in the Arctic Observing Network and Arctic policy

SCICEX planning makes the integration of submarine sampling with AON an important priority and is designed to contribute towards the broader observing goals of clarifying the extent of Arctic change and the processes associated with it. Several decades of submarine sampling in the Arctic have shown that virtually all of the sampling devices that can be deployed on a mooring or drifter can be successfully deployed on a submarine. The submarine also has carried out many of the sampling modes of a surface ship such as vertical profiling and the deployment of swath mapping instrumentation for bottom characterization. SCICEX planning for AON observations recognizes the unique combination of sampling modes made possible by submarines and the economies that can be obtained through interdisciplinary sampling from this platform. The mobility of the submarine remains unparalleled by any existing platform in the Arctic, a dominant factor for many of the scientific results from its sampling. For example, until recently when icebreakers began to venture into the Artic with some regularity, submarine bottom sounding was critical for the details provided to the International Bathymetric Chart of the Arctic Ocean (IBCAO; Jakobsson, this volume). In addition, the ice draft data from submarines remains the standard against which new remotely sensed estimates are compared. The proliferation of moorings and drifting buoys (such as the UpTempO temperature trackers (http://psc.apl.washington.edu/UpTempO/) as well as of AUVs and glider technologies within AON provides the capability of using submarines for adaptive and more detailed sampling of features recorded by the less mobile platforms. This combination would provide a more comprehensive view of the evolution of Arctic Ocean features in space and time than any one mode of sampling could.

This integration of sampling assets is dependent on a parallel integration of organizational structure. Fortunately, this integration exists within AON and its parent activity SEARCH that is part of the Inter-agency Arctic Research Policy Committee (IARPC) activity. IARPC identifies priority observational efforts with the goal of optimizing observational assets with arctic modeling needs (Executive Office of the President, 2013). The multidecadal records of key ice and water property parameters that have been collected by submarines in the Arctic provide some of the few long-term data sets. Thus, while it is not possible to predict the exact scope of the SCICEX program in the future, the continued access of the scientific community to these basic time series that have a consistent collection procedure is likely. Positive indications for this can be found in the Navy's Task force Climate Change and its first major deliverable, the U.S. Navy Arctic Roadmap, released in November 2009. This document guides Navy policy, investment, action, and public discussion regarding the Arctic. It specifically lists Arctic capability in Science & Technology as a needed action item to improve the Navy's ability to operate in the Arctic with the Office of Naval Research as the lead agency. The Roadmap also focuses on Assessment and Prediction – including data gathering through the use of networked observing systems to provide Navy leadership and decision makers with a comprehensive understanding of the current and predicted Arctic physical environment on tactical, operational, and strategic scales in time and space. Each of these actions requires a research, or at least observing component for full implementation. Just as for the IARPC plans, the Navy also anticipates increased international collaboration and the Task Force Climate Change has participated in bilateral international coordination with other Arctic nations, as well as with numerous allied nations. These plans parallel the goals of the Sustaining Arctic Observing Network (SAON) to enhance Arctic-wide, international, observing and synthesis activities.

The decision to support proposed sampling will be made by the SCICEX Interagency Committee (IAC), with concurrence from an identified funding source. Investigators seeking funding for SCICEX-related observations and/or research should contact either the ONR Arctic and Global Prediction Program or the NSF Arctic Observing Network Program to discuss the proposed work and for advice about submitting proposals. Investigators planning a proposal to ONR or NSF should also contact the Technical Director, ASL, to discuss the feasibility of their plans (http://www.csp.navy.mil/asl/index.htm).

7 Appendix – Example scientific results of prior military submarine observations in the Arctic

Past SCICEX and pre-SCICEX submarine cruises have provided key insights to improved understanding of the complex Arctic Ocean environment and the scope of the recent environmental changes there. A brief summary of the important scientific contributions made by submarine cruises include:

Ice Cover

- Sea ice draft data collected since 1958 provide the bulk of our current knowledge of ice thickness over the Arctic basin (McLaren et al., 1990; Wadhams, 1990; Shy and Walsh, 1996).

- First and most definitive evidence of a thinning ice cover (Rothrock et al., 1999a; Rothrock, et al., 1999b; Yu et al., 2004).
- Evidence for recent continued ice thinning (Richter- Menge et al., 2008; Rothrock et al., 2008; Kwok and Rothrock, 2009).
- Integration of submarine data with satellite, mooring data and models (Kwok et al., 2007, 2009; Nghiem et al., 2007; Giles et al., 2008, Melling et al., 2005; Richter-Menge et al., 2006; Rothrock and Zhang, 2005; Maslowski at al., 2007; Lindsay et al., 2009).

Bathymetry

- Previously inaccessible areas of major topographic provinces were mapped. Data contributing to the new International Bathymetric Chart of the Arctic Ocean led to first-order changes in the mapped positions and depths of major bathymetric features (Edwards and Coakley, 2003).
- SCICEX data provided evidence suggesting an approximately kilometer-thick ice shelf covered much of Arctic Ocean during Pleistocene glacial maximum (Polyak et al., 2001; Kristoffersen et al., 2004).
- Discovery of recent volcanic activity along the Gakkel Ridge (Edwards et al., 2001; Müller and Jokat, 2001; Tolstoy et al., 2001).

Hydrography

- Provided definitive, synoptic evidence of upper ocean circulation pathways, and evidence of warming and expansion of Atlantic water as it propagated along basin peripheries and ridges (Morison et al., 1998; Gunn and Muench, 2001).
- Large-scale variations in the salinity of the halocline in the Amundsen and Makarov basins were first observed (Steele and Boyd, 1998; Boyd et al., 2002).
- The accumulated cross-basin data set contributed to defining water mass residence times and circulation (Smith et al., 1999; Kikuchi et al., 2005; Steele et al., 2004; Shimada et al.; 2004; Woodgate et al., 2007).
- Submarine time series data helped to detect multidecadal variability of Atlantic Water in Arctic (Polyakov et al., 2004).
- Data used to validate numerical modeling parameterizations (Karcher et al., 2003; Zhang and Steele, 2007).

Chemistry

- Physical and chemical characteristics of mesoscale eddies, thought to occupy up to 25% of the Canadian Basin, were studied in detail (Muench et al., 2000).
- Renewal time for Atlantic water in the Canada basin was found to be 1 -2 decades (Smethie et al., 2000).
- Estimates for penetration of shelf water to interior (Kadko and Aagaard, 2009).
- Rate of CO_2 uptake by the Arctic Ocean is twice the average for the global oceans (Tanhua et al.; 2009).

Biology

- Pathways for transport of dissolved organic material from shelves to basin were determined (Guay et al. 1999a, b).
- Characterizations of bacterial and archeal assemblages in the Arctic Ocean (Bano and Hollibaugh, 2002; Bano et al., 2004; Kalenetra et al., 2009).

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