Chapter 3: A Science Submarine's Contribution to Priority Research Areas

In the previous chapter, we identified the unique measurement capabilities for a scientific submarine compared to a range of alternative research platforms in the Arctic Ocean and the ice-free oceans. We found that a submarine is unique in its ability to collect high-resolution bathymetric, seismic refraction and reflection, and hydrographic data over the entire Arctic Basin without regard to weather, rough seas, or seasonal changes in the environment. In this chapter, we assess the scientific impact of these capabilities. Consistent with the NSF-planning approach for large facilities we assess these capabilities against the needs of priority scientific agendas. To carry out this analysis, we define the research environment for a submarine by examining a hierarchy of research tasks within the topical areas discussed in the previous chapter. In doing so, we try to answer specifically

- How do current research needs motivate submarine research?
- Considering these needs, what is the specific need for information gathered by a submarine, as opposed to information that might be obtained from other platforms?
- What would be the submarine's contribution to top-level research goals, compared to complementary research activities on different problems, using different platforms or techniques?

Using consensus research agendas, we develop structured problem-solving frameworks in the four research areas discussed in the previous chapter: Arctic climate change and its relationship to global climate change; geologic and geophysical exploration in the Arctic Basin; and understanding the dynamics of the Bering Sea ecosystem.

Following this discussion, the potential submarine contributions to Oceanographic Studies in the Ice-Free Oceans are dealt with separately. The goal of this exercise is to illustrate submarine's scientific impact through its contribution to the natural hierarchy of research tasks within each of the research areas. To carry out this work, we borrow heavily from RAND's strategy-to-tasks analysis (STT),[1] developed to link top-level policy objectives to a wide range of operational tasks. For our analysis, we are interested in the link between top level program goals, scientific questions, and prioritized research tasks.

Because of the interdisciplinary quality of submarine data, this will be an original analysis. Typically, large research facilities are considered against the prioritized needs as defined by individual disciplines (e.g., for a specific type of telescope, or a high-energy particle accelerator). Often, this analysis is coupled to the design process, in which facilities are developed with specific capabilities addressed to specific problems. By comparison, past proposals for a scientific submarine have been largely opportunistic, emphasizing potential windfalls to civilian research to be derived from systems and capabilities intended for military missions (i.e., "swords into plowshares"). To support decisionmaking for civilian expenditures on a scientific submarine program, there is a need for a new approach that evaluates a submarine's contribution to established research goals.

To carry out this analysis, we summarize for each of the three priority research areas the high-level scientific objectives, the strategy the scientific community has chosen to pursue these objectives, and the scientific questions that motivate the key research tasks needed to implement the strategy. We then list the research tasks (i.e., data gathering, analysis, modeling) needed to support the objectives. We draw information from the consensus research agendas of the scientific community. In some cases, there is a natural progression, or hierarchy, to the research tasks (e.g., data gathering that must precede other efforts). In other cases, there is a synergy among the research tasks, allowing diverse approaches to accomplish the top-level objectives. This analysis results in a comprehensive mapping of the research environment where a scientific submarine would operate. In our discussion, we refer to this mapping as the strategies-to-tasks framework for the research area. Using this framework, we characterize the submarine's contribution to priority research areas by assessing its contribution to each of the research tasks. Because the submarine's uniqueness is the primary consideration for the benefits analysis, we rank the submarine's contribution to each task according the following scale:

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[1]David E. Thaler, "Strategies-to-tasks: a framework for linking means and ends," RAND/DRR-243, 1993, 39 pages.

- Submarine data applied to this problem have a number of unique characteristics that would be difficult or impossible to match with other platforms (shaded dark green in this chapter's tables and figures).
- Submarine data applied to this problem may have unique characteristics compared to other platforms (shaded green in this chapter's tables and figures).
- Submarine data applied to this problem may be approximated by other platforms, though there may be differences in quality (shaded light green in this chapter's tables and figures).
- Submarine data are not applicable to this problem (not shaded in this chapter's tables and figures).

Viewed in its entirety, this analysis provides a robust framework to assess the relative importance of the submarine's research contributions. For decisionmakers, this is the foundation for the benefits analysis to compare with the cost information in the following chapter.

Geologic and Geophysical Exploration in the Arctic Basin

To construct a strategies-to-tasks framework for Geologic and Geophysical Research in the Arctic, we use the recommendations from the following scientific community reports:

- Opportunities and Priorities in Arctic Geoscience, National Research Council, 1991.
- Arctic Ocean Research and Supporting Facilities, National Research Council, 1995.
- Ocean Drilling Research, an Arctic Perspective, National Research Council, 1999.
- Summary Report, InterRidge Workshop on Mapping and Sampling the Arctic Ridges, 1998.
- Marine Sciences in the Arctic: A Strategy, a Report to the National Science Foundation, 1999.

The research strategy, outlined in these documents, is a straightforward program of baseline data collection. The research questions that drive this effort are quite general, reflecting a need for basic information rather than collecting data to test specific hypotheses or models. As described above, this effort reflects the primitive state of knowledge regarding the Arctic Ocean basin, arising from the logistical difficulties of performing research in ice-covered seas. These issues are reflected in the NSF's program description, soliciting proposals for geologic and geophysical research in the Arctic:

> Research supported by OPP [the Office of Polar Programs] includes all sub-disciplines of terrestrial and marine geology and geophysics. Special emphasis is placed on understanding geological processes important to the arctic regions and geologic history dominated by those processes.[2]

In this setting, the overall topology of the strategy-to-tasks is one-dimensional: there is a single strategy to accomplish the top-level objective, followed by a sequence of research tasks. Without competing strategies, the priorities for research largely reflect the natural sequence for data collection (e.g., site surveys of the ocean basin will precede drilling and sampling efforts). Moreover, there is a direct connection between data collection efforts and the top-level objective, suggesting a simple approach to identifying the benefits for different data acquisition strategies.

Figure 3.1 illustrates a hierarchy that connects a high-level scientific objective—Fill Longstanding Knowledge Gaps Regarding the Arctic Ocean Basin—with the scientific questions that must be answered to achieve this objective as well as to the measurements needed to answer those questions.

The most important feature of the submarine for geological and geophysical exploration in the Arctic is the capability to collect high-resolution swath bathymetry and sub-bottom profiles over the *entire* Arctic Basin. As indicated in Table 2.1, it would not be feasible to collect a data set of this quality and coverage using alternative platforms such as icebreakers and AUVs. For this reason, we indicate unique characteristics for submarine data applied to two of the research tasks in Figure 3.1. A portion of these data was collected during the SCICEX cruises, with important scientific implications. Building on these results, and previous scientific proposals, it has been recognized that high-quality bathymetric data would have a legacy value and it would make a critical contribution to the high-level research objective of filling in long-standing knowledge gaps regarding the Arctic Ocean basin. If one were to map all regions greater than 100 m depth, this would correspond to an area of 3.65×10^6 km^2. Based on the performance of the SCAMP system, this would

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[2] "Arctic Research Program Opportunities," National Science Foundation Program Announcement, 98-72, 1998.

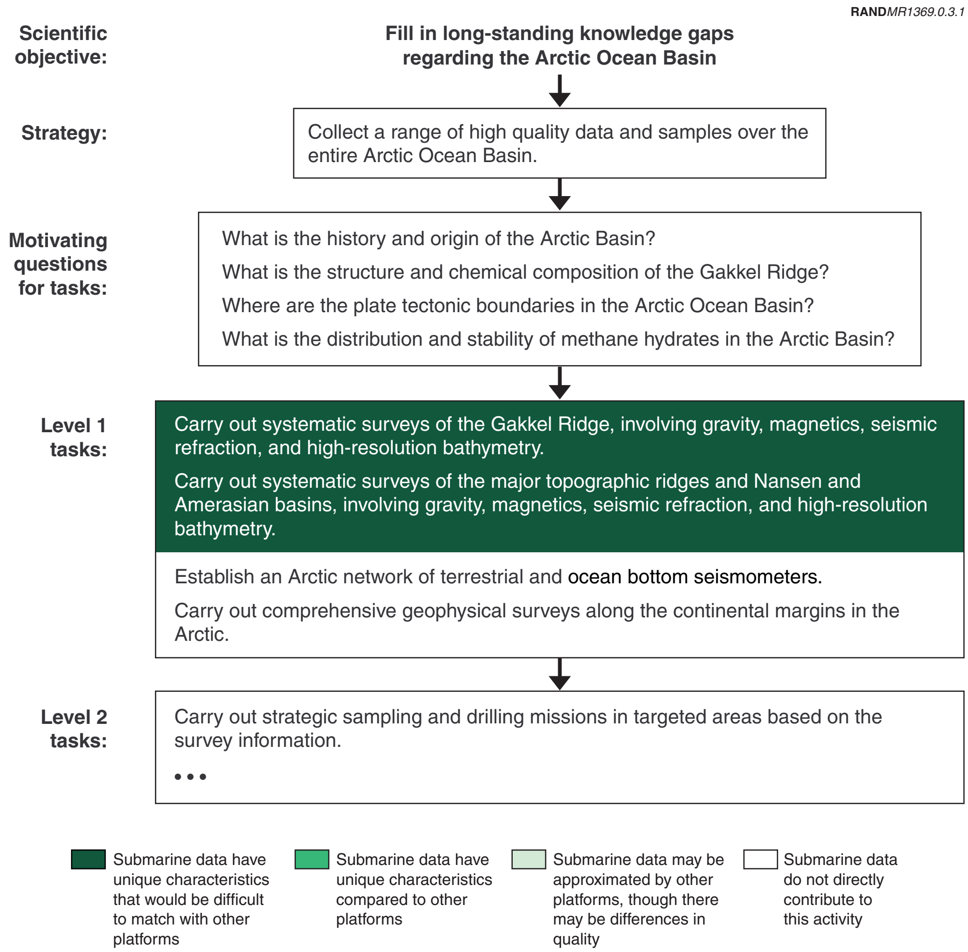

Figure 3.1 Geology and Geophysics Research Objectives and Tasks

require approximately 400 days of data collection. This represents about three years of data collection from a dedicated science submarine.

The submarine's capability to collect seismic refraction and reflection data would also be valuable in this research area, as shown in Table 3.1. While icebreakers have collected these data in the past, a submarine would offer at least one important advantage: the ability to collect data over a continuous region with precise control of the navigational tracks. Submarine gravity measurements would provide higher resolution data, compared to aerial or satellite surveys that are currently available. If these data were collected with bathymetric surveys, it would allow a straightforward and accurate association between the data sets, which is valuable for geologic and geophysical studies in the ocean basins.

Scientific objectives	Research tasks	Submarine measurements								
		Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Fill in long-standing knowledge gaps regarding the Arctic Ocean Basin	Carry out systematic surveys of the Gakkel Ridge, involving gravity, magnetics, seismic refraction, and high-resolution bathymetry.	X			X	X				
	Carry out systematic surveys of the major topographic ridges and Nansen and Amerasian basins, involving gravity, magnetics, seismic refraction, and high-resolution bathymetry.	X			X	X				

NOTE: Boxes not filled are not applicable to this research objective.

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- Submarine data have unique characteristics that would be difficult to match with other platforms
- Submarine data have unique characteristics compared to other platforms
- Submarine data may be approximated by other platforms, though there may be differences in quality
- Submarine data do not directly contribute to this activity

Table 3.1 Contribution of Submarine Capabilities to Research on Geologic and Geophysical Exploration

In summary, submarine data would make a number of unique and important contributions to Geologic and Geophysical Exploration in the Arctic Basin. The submarine would also have a relatively large relative impact in this field, because of the hierarchy of current research problems.

Climate Change in the Arctic

To construct a strategy-to-tasks framework for Climate Change in the Arctic, we consulted the recommendations from the following scientific community reports:

- *Marine Sciences in the Arctic: A Strategy,* a Report to the National Science Foundation, 1999.
- *Arctic Climate System Study Implementation Plan,* World Climate Research Programme, 1999.
- *Toward Prediction of the Arctic System: Predicting future states of the arctic system on seasonal-to-century time scales by integrating observations, process research, modeling, and assessment; a science plan for the National Science Foundation Arctic System Science* (ARCSS) *Program*, 1998.
- *The Arctic Paleosciences in the Context of Global Change Research*, 1999.

The analysis was also informed by plans for the U.S. Global Climate Change Research Program, which includes research in Understanding the Earth's climate system, biology and biogeology of ecosystems, composition and chemistry of the atmosphere, paleoenvironment and paleoclimate, human dimensions of global climate change, and global water cycle. Each of these areas includes Arctic climate research.[3] We also examined the World Climate Research Program, where the Arctic Climate System Study is one of five major projects. The others include Global Energy and Water Cycle Experiment (GEWEX), World Ocean Circulation Experiment (WOCE), Stratospheric Processes and their Role in Climate (SPARC), and Climate Variability and Predictability (CLIVAR).

While there are a large number of publications outlining climate research issues in the Arctic, we chose the above publications because they articulate organized research plans to be executed by NSF and the international scientific community. In general, these define the top tier of research activities; a large number of research plans have been written to detail the activities outlined in these publications.

Together these publications define a comprehensive, systems-based strategy for studying Arctic climate as shown in Figure 3.2. In this context, "system" refers to the collective interactions and feedback mechanisms between the ocean, sea ice, atmosphere, landmass, biomass, and freshwater that control the Arctic climate. At the center is a focus on modeling, with the goal of developing an improved predictive capability for the behavior of the Arctic climate. In part, the modeling effort is supported by accurate historical data, describing changes in Arctic climate over the past 65 million years. Hence, there is a strategy to document the climate history of the Arctic. To strengthen

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[3]For FY 2000, the National Science Foundation designated $181.7 million as part of the U.S. Global Climate Change Research Program. The Arctic component was included in the Arctic System Science program, with $13.8 million in funding.

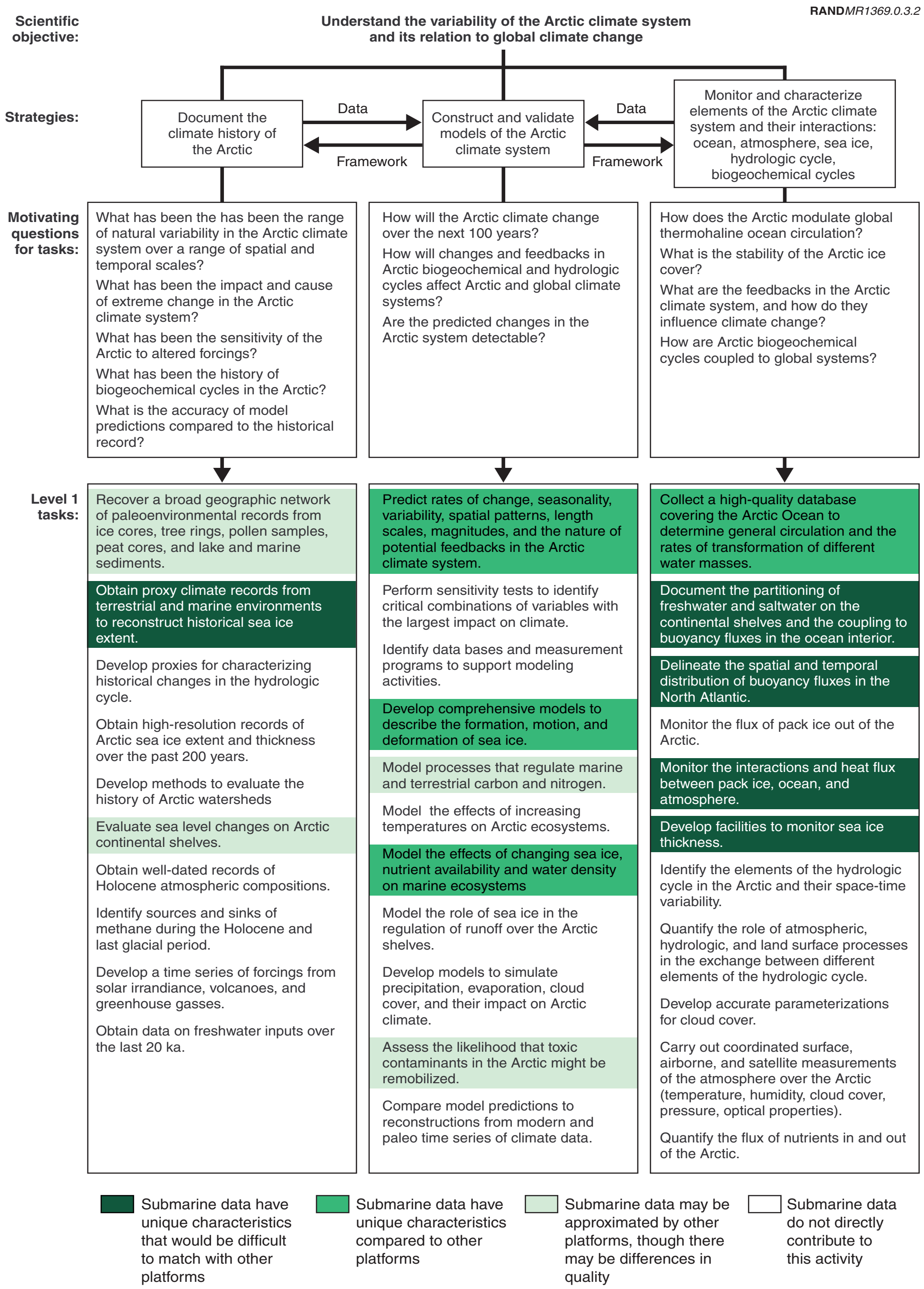

Figure 3.2 Climate Change Research Objectives and Tasks

present-day models, and to provide a basis for future predictions, there is a need for detailed monitoring of the current Arctic climate system. Hence there is a strategy to monitor and characterize elements of the Arctic climate system and their interactions: ocean, atmosphere, sea ice, hydrologic cycle, biogeochemical cycles.

Unlike the framework for geology and geophysics, climate change research in the Arctic requires coordination over a wide range of disciplines and facilities to achieve the top-level objective. (See Appendix C for a discussion of current research activities and infrastructure in the Arctic.) Given the synergy between the research strategies (e.g., data collection and monitoring to support modeling), there is a complex prioritization for individual tasks. In such an environment, additional policy and program concerns play an important role in focusing decisionmaking on individual research efforts and facilities. Important considerations include the opportunities for synergy, balance of funding between disciplines, and maximizing the value of existing facilities.

For climate change research, the most important feature of the submarine is the capability to collect data over broad areas of the Arctic Basin at all times of year. Of particular importance are hydrographic measurements in the upper ocean (temperature/salinity profiles), detailed mapping of ice draft and structure, and high-resolution bathymetric surveys. Applied to the following scientific tasks, submarine data would have unique characteristics with important research implications:

- Document the partitioning of freshwater and saltwater on the continental shelves and the coupling to buoyancy fluxes in the ocean interior.
- Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic and Greenland Sea.
- Monitor the interactions and heat flux between pack ice, ocean, and atmosphere.
- Develop facilities to monitor sea ice thickness.
- Obtain proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent.

As shown in Table 3.2, the first three tasks involve hydrographic measurements, with spatial mapping of temperature and salinity variations in the upper ocean. For this work, the submarine's mobility and access would be particularly valuable because the research requires data collection over broad areas, under conditions that often preclude surface operations. It is notable that the quality of these submarine data would be inferior to those that might be collected by a surface ship because of differences in the sensor technology between these platforms, as shown in Table 2.1. This comparison

Table 3.2 Contribution of Submarine Capabilities to Research on Climate Change in the Arctic

Scientific objectives	Research tasks	Submarine measurements: Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Understand the variability of the Arctic climate system and its relation to global climate change	Document the partitioning of freshwater and saltwater on the continental shelves and the coupling to buoyancy fluxes in the ocean interior.		X	X						
	Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic.		X	X					X	
	Develop facilities to monitor sea ice thickness.							X		
	Monitor the interactions and heat flux between pack ice, ocean, and atmosphere.		X	X				X	X	X
	Obtain proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent.	X				X				
	Collect a high-quality database covering the Arctic Ocean to determine general circulation and the rates of transformation of different water masses.	X	X	X					X	X
	Develop comprehensive models to describe the formation, motion, and deformation of sea ice.							X	X	
	Model the effects of changing sea ice, nutrient availability, and water density on marine ecosystems.		X	X			X	X		X
	Model processes that regulate marine and terrestrial carbon and nitrogen.		X							
	Assess the likelihood that toxic contaminants in the Arctic might be remobilized.	X	X						X	
Understand the variability of the Arctic climate system and its relation to global climate change	Recover a broad geographic network of paleoenvironmental records from ice cores, tree rings, pollen samples, peat cores, and lake and marine sediments.	X			X	X				
	Evaluate sea level changes on Arctic continental shelves.	X				X				

NOTE: Boxes not filled are not applicable to this research objective.

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- Submarine data have unique characteristics that would be difficult to match with other platforms
- Submarine data have unique characteristics compared to other platforms
- Submarine data may be approximated by other platforms, though there may be differences in quality
- Submarine data do not directly contribute to this activity

Note: An x indicates the types of submarine data that are pertinent to specific research tasks.

illustrates the importance of context for the benefits analysis: The potential benefits from a scientific submarine are associated with specific capabilities applied to specific problems.

A number of platforms can collect data to address the fourth task, developing facilities to monitor sea ice thickness. These include moored upward-looking sonar, surface wave propagation experiments, acoustic propagation measurements, radar imagery, and submarine measurements. However, the other platforms have difficulty matching the most important characteristic of the submarine data, which is the capability to make detailed maps of ice thickness across the Arctic Basin. Repeat transects across seasons and years would provide unprecedented fine-scale information for studying the temporal evolution of ice thickness. The fifth problem, obtaining proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent, overlaps with the Geologic and Geophysical Exploration in the Arctic, as it involves detailed mapping of the ocean bottom to identify features such as glacial scour and paleocurrent indicators.

Within the strategies-to-tasks framework for Climate Change Research in the Arctic, there are a number of areas in which a submarine would contribute, but at a lower level of impact, because alternative platforms would make a comparable contribution to the research task.

Viewed in the broadest perspective, climate change research clearly requires a diverse range of platforms and strategies to achieve the top-level scientific objective. In this setting, the nature of the submarine contributions is also diverse. While the dedicated science submarine would make fundamental contributions for some of the tasks, its impact in other areas would be less profound. Thus, the final assessment of the submarine benefits in this area depends on priorities assigned to these research efforts. Specifically, would the submarine make a unique contribution to high-priority tasks? We assume that this final prioritization would be carried out by the scientific community, working with the civilian science agencies.

Finally, military submarines could also contribute to the measurements needed for climate change research as part of their operational missions. The potential value of these data was emphasized in one of the recommended mission profiles in the *SCICEX 2000* workshop report. For climate change research, the most important data include temperature/salinity profiles measured with expendable probes and ice draft measurements obtained from the submarine's topsounder.

Understanding the Dynamics of the Bering Sea Ecosystem

To assemble a strategies-to-tasks framework for this research area, we used the recommendations and analysis from the following documents

- *Draft Bering Sea Ecosystem Research Plan*, September 1998, Interagency document prepared by NOAA, Department of Interior and Alaska, Department of Fish and Game.
- *The Bering Sea Ecosystem*, National Research Council, 1996.

The interagency Draft Research Plan represents a consensus distillation for a wide range of previous planning efforts. By comparison the National Research Council report describes the scientific challenges for developing a more effective ecosystem management practices. Together, these reports suggest a huge range of research activities which we have distilled, with some abbreviation, in Figure 3.3.

The goal for this research is to collect a large amount of information on the properties of the Bering Sea ecosystem to refine predictive models of ecosystem behavior in response to external changes (e.g., climate change, fishing, changes in species populations). In this case, the application for the models, and scientific understanding is to improve the effectiveness of ecosystem management practices. Like the climate change problem, the tasks span a huge range of disciplines and research activities, suggesting a similar need for coordination and prioritization to increase the effectiveness of the overall research effort.

Table 3.3 Contribution of Submarine Capabilities to Research on the Dynamics of the Bering Sea Ecosystem

Scientific objectives	Research tasks	Submarine measurements								
		Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Improve the understanding of ecosystem processes in the Bering Sea to support more effective ecosystem management practices	Collect data on ice condiditons and hydro-graphy in the Bering Sea.		X	X				X	X	
	Determine how sea ice, sea surface temperature, and the extent of the cold pool affect the transfer efficiency of primary production to the pelagic and benthic food webs.		X	X			X	X	X	X
	Establish baseline conditions for the physical environment.	X	X	X					X	X
	Monitor contaminant levels (chemical and debris).		X							

NOTE: Boxes not filled are not applicable to this research objective.

RANDMR1369.0.T3.3

- Submarine data have unique characteristics that would be difficult to match with other platforms
- Submarine data have unique characteristics compared to other platforms
- Submarine data may be approximated by other platforms, though there may be differences in quality
- Submarine data do not directly contribute to this activity

Note: An x indicates the types of submarine data that are pertinent to specific research tasks.

In this research area, the submarine's strongest feature is its ability to navigate and make measurements under the ice. Similar to climate change research in the Arctic Ocean, there is a need for hydrographic and ice draft measurements in the Bering Sea, as shown in Table 3.3. The principal challenge for this work is that much of the Bering Sea may be too shallow for safe submarine operations (40 percent is less than 100 m deep). In addition to the hydrographic and ice measurements, which were demonstrated during SCICEX, submarine monitoring of biological features would also be unique, if it was performed in ice-covered seas. Examples include water sampling from specific oceanographic features and mapping fish and zooplankton populations using the submarine's sonar systems. In this application the submarine's quietness could add importantly to its data collection capabilities. The last item has been proposed for a scientific submarine, yet it was not demonstrated during the SCICEX cruises. In part, this reflects classification concerns regarding the submarine's onboard sonar systems. With this background, the submarine's primary impact would be associated with the following tasks:

- Collect data on ice conditions and hydrography in the Bering Sea
- Determine how sea ice, sea surface temperature, and the extent of the cold pool affect the transfer efficiency of primary production to the pelagic and benthic food webs.

Given the breadth of the required research effort, the final assessment of the submarine benefit clearly requires a top-level prioritization for all of the research tasks.

Contributions to Oceanographic Studies in the Ice-Free Oceans

Because of the size and scope of this research area, we use a different approach to analyze the potential submarine benefits. As noted previously, Oceanography in the Ice-Free Oceans addresses a diverse research agenda, utilizing a vast array of data collection facilities. Viewed from a top-level perspective of a strategies to task framework, it is difficult to assess to contribution of a single platform (such as a submarine) to such a large research problem. More important, the programmatic decisionmaking in this area is distributed over a much greater number of agencies, disciplines, and stakeholders compared to the other three research problems that we have considered (Climate Change in the Arctic, Geologic and Geophysical Exploration in the Arctic, and Understanding the Dynamics of the Bering Sea Ecosystem).

To consider the potential submarine contributions, we examine the proposed research tasks for a SSN 637-class submarine in the ice-free oceans, identified in the UNOLS report *A Nuclear-Powered Submarine Dedicated to Earth, Ocean, and Atmospheric Research.* Noting the comparisons in Table 2.2, we identify the submarine's potential for unique contributions for each of these problems.

We conclude with observations about the submarine capabilities that would have the largest impact on oceanographic research.

(1) Studies of deepwater formation in the North Atlantic.

This task, which addresses an important question in climate change research, was discussed in the strategies-to-task framework for Climate Change in the Arctic: Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic. As noted in that discussion, a submarine would provide unique data for this problem.

(2) Documenting the evolution of the hydrographic structure of the upper ocean under a hurricane.

While a large number of assets are deployed to measure the properties of hurricanes from above (airplanes and satellites), there is comparatively little understanding of the exchange of energy between hurricanes and the underlying ocean. It has been postulated that such information would improve forecasting models for the strength, evolution, and tracking of hurricanes. In principle, a submarine has a unique capability to collect hydrographic data under a moving hurricane. Clearly, there would be significant logistical considerations associated with these deployments.

(3) Carry out high-resolution ocean acoustics experiments to monitor fronts in coastal waters, internal waves, and ocean bottom reverberations.

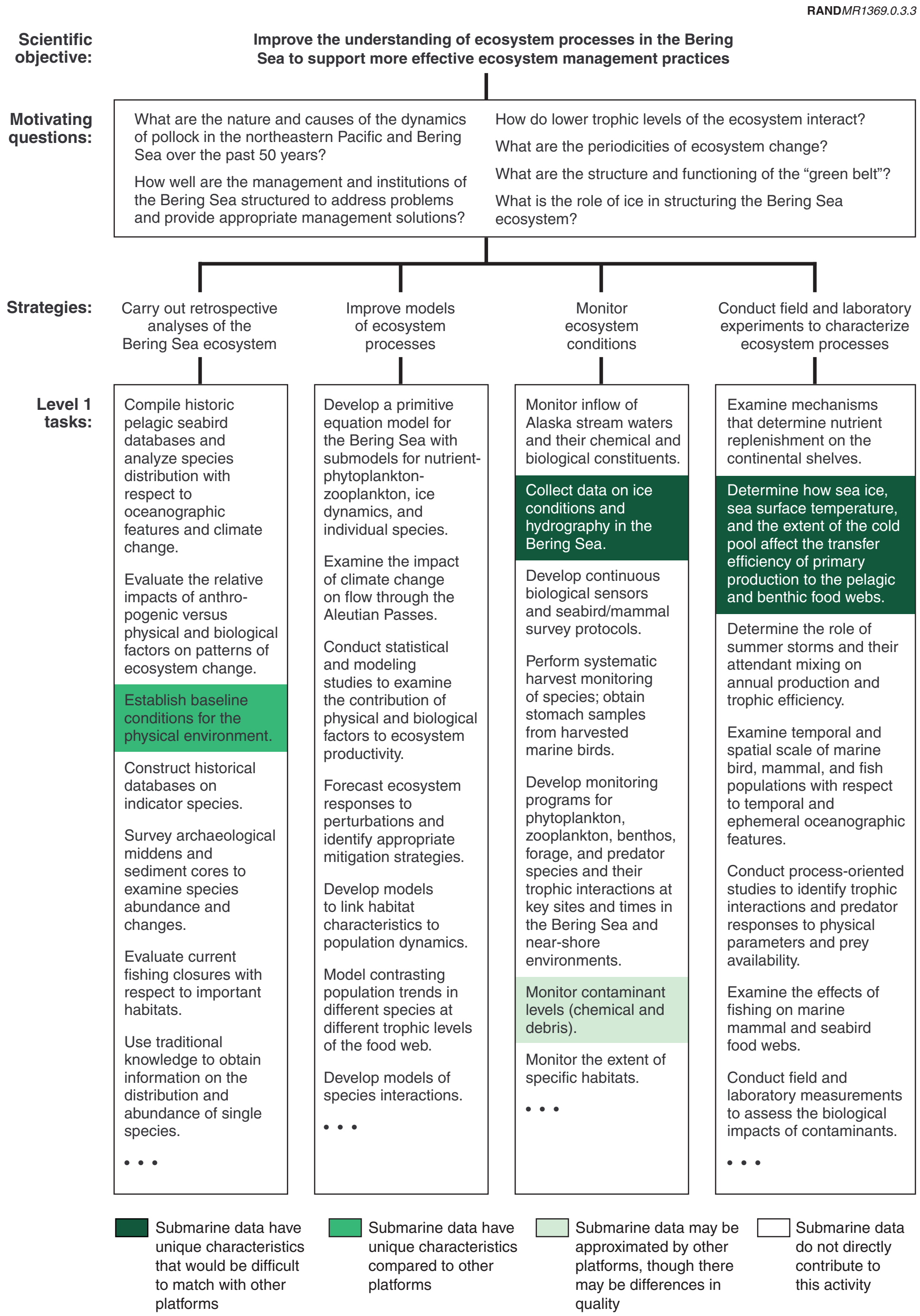


Figure 3.3 Bering Sea Ecosystem Research Objectives and Tasks

The onboard sonar arrays on a nuclear-powered submarine would provide a novel capability for ocean acoustics experiments. Compared to other facilities for acoustic measurements, a submarine has three principal advantages: a large effective aperture for the sonar array, a capability to track hydrodynamic features in the ocean, and low ambient noise levels. To be useful, these measurements would require full access to the acoustic waveforms from the submarine sonar systems. Thus, it may not be possible to perform this research in an unclassified setting.

(4) Carry out geophysical surveys off Antarctica.

Because of the remote setting, and the presence of drifting ice bergs, there have been relatively few geophysical surveys in the seas surrounding Antarctica. In this environment, a submarine would have unique capabilities to collect swath bathymetry and gravity data over broad areas. Working with an icebreaker, it could also collect seismic refraction and reflection data. However, policy concerns associated with the Antarctic Treaty may limit submarine deployments below 60º S. These issues are discussed in detail in Appendix F.

(5) Conduct hydrographic measurements in remote regions, especially south of 60º S.

There is a growing interest in detailed hydrographic data from all the world's oceans to support improved climate and oceanographic models (e.g., temperature/salinity profiles and current data). In remote regions, these data have historically been collected by "ships of opportunity," leading to databases with uneven quality and spatial distributions. Because a submarine can cruise faster than a surface ship (25 knots compared to approximately 15), through all weather, it has been suggested that a submarine could collect high-quality data from under-sampled regions. However, in recent years the unique quality of these submarine data has diminished because of the development and deployment of automated profilers throughout the oceans.

Considering the above issues, the most important feature of the submarine for research in the ice-free oceans is the capability to work in rough seas. Thus, the submarine would make the most unique contribution to the first and second research problems. Similar to the strategy to task discussion, the overall submarine benefit depends on the prioritization for these research efforts by the scientific community and the civilian science agencies.

Additional Considerations

In the preceding discussion, we have considered a submarine's capability to collect a range of scientific data sets against the needs of consensus research agendas. To inform a top-level consideration of the benefits associated with a scientific submarine, this analysis identifies scientific problems where a submarine would provide unique data. In this section, we discuss additional issues which may have some implications for the benefits of a science submarine. These are

- Technological developments in autonomous underwater vehicles (AUVs);
- Existing oceanographic databases; and
- Treaties and international agreements.

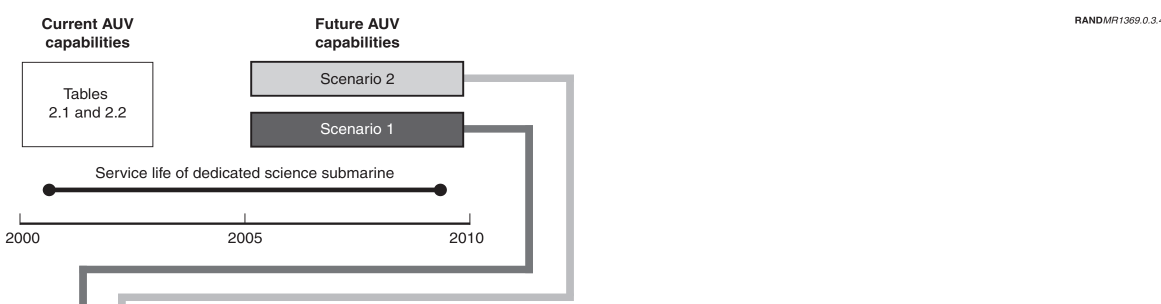
In general, these issues have the potential to affect the benefits of a scientific submarine. Specifically, technological advances in ocean sensors may reduce a submarine's unique contributions; international agreements may limit the operations of a nuclear-powered submarine; and newly declassified oceanographic databases may redefine priority research areas and thus enhance or decrease the impact of a science submarine's contributions. Because these effects are difficult to predict, they have not been incorporated in the above analysis of the submarine's contribution to scientific research. However, they may play an important role in the assessment of the submarine benefits, and thus, they are discussed in separate sections below.

Developments in Autonomous Underwater Vehicle Technology

The discussion so far has identified the unique capabilities of a dedicated science submarine given the submarine's current capabilities and that of alternative platforms for Arctic research. The last decade, however, the has seen the rapid development of AUVs, driven by progress in small, cheap and powerful computer technology; artificial intelligence and novel automatic control algorithms, information networking breakthroughs; and new materials for structural and sensor systems. A variety of these self-contained, robotic submersibles have been prototyped and demonstrated, and a few have even performed useful operational missions on an ongoing basis. The rate of progress in these AUV systems suggest that in the future they could potentially collect many of the measurements currently unique to a dedicate science submarine.

Predicting the rate of technological progress is difficult, especially in areas where the state of the art is advancing rapidly. Proponents of these AUV systems suggest that they could provide many of the capabilities we identify as unique to a dedicated science submarine, at a minimum of five to ten years later than such observations would be available with such a submarine. There are significant, ongoing research efforts aimed at developing AUVs capable of long-transect hydrographic measurement in the Arctic Basin. The individual components for this AUV have been successfully tested by researchers at the Monterey Bay Aquarium Research Institute, and a full-scale Arctic field test is scheduled for spring of 2001. Decisionmakers should properly view with some skepticism any claims about the date at which potential revolutionary, but not yet proved, capabilities of new technology systems will become available. Nonetheless, the potential of these AUVs is sufficient to warrant the serious attention of decisionmakers concerned with a dedicated science submarine.

The uncertain, yet potentially significant, future capabilities of AUVs presents decisionmakers with a classic problem of balancing today's "bird-in-the-hand" against potentially promising future "birds-in-the-bush." To frame the contours of this decision, we present a simple scenario analysis as sketched in Figure 3.4. Tables 2.1 and 2.2 described the current capabilities of AUVs as



Platforms	Weather	Seasons	Type of measurement								
			Bathymetry and bottom profiling via sonar	Water sampling for chemical and microbiological analysis	Temperature and salinity profiles	Gravity and magnetics measurements	Seismic refraction	Biological monitoring via sonar	Ice draft and structure	Measurements of current	Optical properties of the water column; ambient light levels
Submarine	Any	All	Broad areas with high S/N	Broad areas at cruising depth, marginal labs	Broad areas to 1,000 m	Broad areas, with high S/N; coregistered with bathymetry	Broad areas with high S/N	With tracking over broad areas	Over broad areas	Over broad areas at cruising depth	Over broad areas at cruising depth
Current AUV/ROV deployed from ice camp or icebreaker	Any	All	Limited area; best with ROV	Limited capability	To sea floor; over cruising range	Magnetic surveys feasible over limited areas; gravity under development	No	Proposed	High resolution, over cruising range	To sea floor over cruising range	To sea floor over cruising range
Best case AUV/ROV in 2010	Any	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible

Equivalent to submarine; Degraded capability compared to submarine; Enhanced and degraded compared to submarine; No capability; Enhanced capability compared to submarine

Figure 3.4 Comparison of Submarine with Two Scenarios for Capabilities of Future AUVs

understood from actual operational experience. Over the next 10 years, AUVs may or may not acquire a broad range of additional capabilities. Table 3.4 shows two scenarios spanning a range of possibilities, based on forecasts of potential technological trajectories. At one end of the spectrum (labeled Scenario 1), AUV technology will remain relatively unchanged compared to the submarine. At the other end of the spectrum (labeled Scenario 2), AUVs could plausibly exceed submarine capabilities in any and all measurement areas. This end of the spectrum would come about with significant improvements in AUV range and continued miniaturization of onboard instrumentation. These new capabilities could overlap with the lifetime of the *L. Mendel Rivers* as a scientific submarine, or not arrive until after its retirement—if at all.

One of the key factors that will influence whether highly capable AUVs will come about is the level of government support for the development of AUV technology. However, there may be, as in any technology development program, unforeseen technical or operational problems. Thus, in weighing the benefits of a dedicated scientific submarine, decisionmakers must consider the funding that may be available for AUV technology and the rate of advance of that technology against the cost of delay in collecting data on the Arctic. Such delay could be costly if data collected in the near term could cause significant changes in policy toward climate change, fisheries management, or other issues.[4] In the scenario where the rate of technology advance for AUVs is rapid, the unique benefits of the submarine will be relatively less. In the scenario where the rate of AUV technology advance is slow and the cost of a delay in acquiring information is high, the value of the submarine is relatively large. Appendix D provides a review of recent progress in AUV technology, but a full assessment of the costs and benefits of relying on future AUVs as a substitute for a dedicated science submarine is beyond the scope of this study.

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[4]Studies on the value of scientific information to climate change policy (see for instance, S. C. Peck and J. T. Teisberg, "Global Warming Uncertainties and the Value of Information: An Analysis Using CETA," Resource and Energy Economics, 15, 71–97, 1993, or R. J. Lempert, M. E. Schlesinger, S. C. Bankes, and N. G. Andronova, "The Impacts of Climate Variability on Near-Term Policy Choices and the Value of Information," Climatic Change, 45:129–161, 2000) suggest that the value of such near-term information can be on the order of several tens of billions of dollars. It is important to note, however, that such studies address the aggregate benefit of all scientific information on climate change, not information on climate change in the Arctic.

Existing Oceanographic Databases

The existence of a substantial body of previously classified data on the Arctic region could also influence the benefits of a dedicated science submarine. Much of this data has been collected by Navy submarines over the past three decades. These data are only now being declassified, converted to digital format, and analyzed. A clearer understanding of what data already exist could affect an assessment of the need for a dedicated science submarine.

How might these data affect the potential benefit of a science submarine? Since virtually all of these data are time sensitive, it is unlikely that their availability would preempt the need for the kind of data gathering missions a dedicated science submarine could perform. Instead, the most likely effect would be to redefine critical polar research areas, which could alter the fit between a submarine's unique capabilities and the scientific community's priority research agenda. Knowledge about the Arctic environment could be enhanced substantially and previously undiscovered or poorly understood problems or conditions could displace other issues at the top of the research agenda.

Historically, scientific databases of the world's oceans have been sparse and uneven because of the sheer size of the areas involved, the cost of operating many platforms, and the remoteness or extreme weather conditions of many locations. Additionally, a second challenge has been archiving, consolidating, and distributing the vast amounts of data that could be made available. Two recent developments are rapidly changing this situation. The first is the great concern within the last decade about global climate change, which has resulted in a concerted international effort to collect and archive oceanographic data over the entire globe. At present, considerable progress has already been made on defining and implementing the technical systems necessary to carry out such ongoing global synoptic observations, for example through the United Nations' Global Ocean Observing System and Global Climate Observing System programs. Within the United States, the U.S. Global Change Research Program has spurred the collaboration of many diverse efforts among federal, private, and academic institutions to build an integrated ocean observing system, and much of this is now largely being guided by the National Oceanographic Partnership Program. A large part of this effort is devoted to designing state-of-the-art integrated data management and distribution systems. As part of this, significant effort has been directed toward centralizing the archiving of previously recorded databases, much of which have not hitherto been publicly available.

The second major development concerning oceanographic databases has resulted from the information-technology revolution. The advent of cheap, high-speed processors, large memory capacities, new storage devices such as CDs, and large bandwidth communication systems and satellite links are revolutionizing the capacity for recording, storing, and transferring data. In particular, the rapid development of the World Wide Web has made it possible to archive and distribute large volumes of data publicly with ease. In fact, most U.S. national earth science databases, and many of the international ones, are already accessible from centralized Web sites, and further consolidation is continuing at a rapid pace, with search engines and depositories for “metadata” (i.e., data about data) now becoming widespread as well.

While it is uncertain just how much these data will add to scientific knowledge of the Arctic region, we do know that with the exception of certain kinds of mapping information, all of the newly declassified data are time sensitive. That is, their existence is not likely to preempt the need for updated measurements in the same areas. Furthermore, the kind of high-resolution bathymetric mapping that represents one of the submarine’s unique capabilities is unlikely to be duplicated in any of the data now being released, for the simple reason that the technology for high-resolution bathymetric mapping did not exist when these data were created.

International Treaties Governing Antarctica

A final caveat involves political considerations associated with Antarctica. Though we have not considered them in this study, there are potential scientific benefits to using a dedicated scientific submarine to perform oceanographic and geophysical research in the oceans surrounding Antarctica. Scientific studies, and exploration in general, of this region are sparse and have been historically hampered by its remoteness and extreme weather conditions. The physical conditions in the seas surrounding Antarctica are in fact so hazardous that large areas are bathymetrically uncharted, and even the location of the continental margin is unknown in places. Operation of surface research vessels is often restricted to only a few months per year. While it would be feasible for an SSN 637-class submarine to operate in these waters, there could be important policy implications that would limit these operations because of requirements from the Antarctic Treaty, as discussed in Appendix F.