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Innovations in marine technology and potential needs for Arctic governance

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Abstract The Arctic is a region of major significance in the Earth system, particularly important for global climate and international maritime governance. As human activity, relying on manufactured equipment, steadily increases in the Arctic, technological innovations for marine equipment must support the gradually more stringent requirements for future Arctic governance. In this review, four categories of innovations are analyzed, namely: innovations driven by traditional thinking, innovations for environmental protection, innovations for practical application, and innovations for observing information systems. Two examples of international regulations, the Polar Code (adopted in 2014) and the International Standard for Arctic offshore structures of the International Organization for Standardization (ISO 19906, first published in 2010), are selected to illustrate successful international cooperation efforts for Arctic marine innovation. This work provides a basis for discussion on technology development, governance efficiency, and international cooperation in the Arctic.

Keywords **innovation, polar marine technology, Arctic governance, environmental protection**

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1 Introduction

The environmental, societal, and economic impact of human activities does not only affect densely populated regions on Earth, but also extends to remote areas. Anthropogenic global warming modifies the Arctic climate more rapidly than anywhere else. Conversely, because of the central role of the Arctic in the planetary climate system, the impact of human activity growth in that region is global.

Recently, marine technological innovations have induced a notable increase in human activities in the Arctic, pertaining notably to shipbuilding. Moreover, such innovations are important tools for international Arctic governance. By correlating marine technology development with the material requirements for Arctic economic development and governance, four categories of technology and equipment innovations used in the Arctic Ocean are identified: innovations driven by traditional thinking, innovations for environmental protection, innovations for practical applications, and innovations for observing information systems. To overcome the challenges encountered in a marine environment, innovative design for technology and equipment is needed.

In this review, we analyze the International Code for Ships Operating in Polar Waters (hereafter Polar Code, https://www.imo.org/en/OurWork/Safety/Pages/polar-code.aspx), adopted in 2014 by the International Maritime

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Organization (IMO), and a standard developed by the eighth working group (WG8) of the International Organization for Standardization (ISO), the ISO 19906 International Standard for Arctic offshore structures, published in 2010 (https://www.iso.org/standard/33690.html) and revised in 2019 (https://www.iso.org/standard/65477.html). We also assess the main innovations in marine technology and equipment in relation to the increasing need for more efficient Arctic governance. Finally, we discuss international cooperation for Arctic marine technology innovation and equipment development.

2 Innovations driven by traditional thinking

In this category, equipment and materials are new or regularly upgraded, but underlying ideas and purpose remain traditional, i.e., nearly identical to those of marine equipment builders of the past centuries: (1) to enhance human strength, power, exploration capabilities, and ability to work in severe environments; (2) to provide material support and alleviate the severity of manual labor; (3) to upgrade marine equipment safety; and (4) to find and exploit natural resources for human benefit. Traditional thinking for innovation consists, for example, of optimizing vessel design and operation by developing new types of steel to strengthen ship hulls, new materials to improve icebreaking ability, more powerful engines to enhance sailing ability, or new energy supplies to increase the operational range.

This concept appears to contain a contradiction, because innovation is not generally associated with traditional thinking. However, technological advances do not necessarily involve drastic changes, but they can also be applied incrementally, by upgrading existing designs without abandoning traditional approaches. Many current innovative resources used for marine equipment in the Arctic Ocean fall into the “incremental advances” category.

The Polar Code, the ISO 19906 standard, and additional regulations for offshore oil and gas drilling platforms show that most design changes aim at improving equipment reliability and personnel safety. They represent traditional innovations welcomed by ship owners and crews. In the traditional model, environmental degradation caused by the equipment is mostly controlled. When negative impact on the environment is unavoidable, a higher regulatory standard for environmental protection must be implemented. For example, after maritime accidents, new ship or platform design regulations are added or the existing regulations are strengthened by additional mandatory requirements.

Because China is not an Arctic country, there are few possibilities in China for polar marine technological innovations driven by traditional thinking. Therefore, Chinese innovations should benefit from the expertise of other countries. Alternately, Chinese innovation knowledge acquired in winter in low-temperature regions such as Bohai Sea (Wang et al., 2012) are applicable to the Arctic.

3 Innovations for environmental protection

In the Polar Code and the ISO 19906 standard, stringent requirements for environmental and ecological protection (Karahalil and Ozsoy, 2020) were established to account for the fragility of the Arctic biome and to address cleaning operation difficulties in case of oil spill or pollution discharge. Moreover, as part of global policies for climate change mitigation and emission reduction, requirements on marine equipment design and manufacturing have been strengthened to reduce exhausts and carbon emissions from polar ships and offshore engineering equipment. Such innovations aim primarily at limiting negative externalities by developing alternative materials and adopting new protocols to reduce waste dumping and pollutant emissions. For example, heavy oil is gradually replaced by less polluting fuels, and international regulations forbid the release or leaking of toxic liquid substances into the Arctic marine and frozen-soil environments. On the one hand, innovation must comply with Arctic governance regulations, especially for environmental protection; on the other hand, it should provide solutions to limit equipment costs and ensure commercial profitability.

Polar waters are highly sensitive to environmental contaminants. Climate warming strongly influences the sea-ice cover duration and extent. Global efforts to reduce emissions and to mitigate climate warming are important to prevent the accelerated melting of polar ice, but efforts to mitigate climate warming impact on marine life in polar waters, where intricate relationships connect invertebrates and mammals, are equally essential. Therefore, ships currently operating in Arctic waters must not only comply with pollution prevention requirements from the International Convention for the Prevention of Pollution from Ships (MARPOL), but should also consider carbon and gray water emissions, anticipate a proposed ban on heavy oil, improve their abilities to recover pollutants, and implement underwater noises control. These strict constraints are challenging for ship design. Pollution prevention requirements cause increased costs, affecting the shipping economy and the willingness of ship-owners to operate in the Arctic. Thus, the objective of innovation for environmental protection is to discover new materials and technologies to meet the requirements of the Polar Code in MARPOL, while maintaining the building costs (or limiting their increase) and the original capabilities and functions of the ship. The shipping industry is gradually responding to the Polar Code requirements that prohibit discharge of oil, oily mixtures, toxic liquid substances, or mixtures containing toxic substances into Arctic waters.

During the 60th meeting of the IMO Marine

Environmental Protection Committee, significant progress was made on drafting technical measures to reduce exhaust emissions and air pollution from international shipping, including mandatory texts establishing an Energy Efficiency Design Index (EEDI) for new ships within the legal framework of MARPOL Annex VI. Such progress constitutes a major improvement for environmental protection, although reducing exhaust emissions and air pollution is a markedly more difficult task than improving the safety of personnel and ships in sea-ice environments. Ships built in accordance with the EEDI might lack sufficient power to navigate in the inhospitable Arctic environment, for example to maintain normal speed or to progress in turbulent wind and rough sea conditions. Therefore, ship design innovations must successfully balance engine power with EEDI energy efficiency requirements to ensure proper ship operation in cold Arctic regions.

The Arctic environment is more vulnerable to pollution than temperate regions. Therefore, structures intended for Arctic operations should be optimally designed to minimize their pollution potential while maintaining reasonable operability. As an example for the similar Antarctic environment, a new class of icebreaking polar research vessels incorporates innovative technologies for fuel efficiency, noise reduction, and protection of the polar region (Rogan-Finnemore et al., 2021).

Compliance with ISO 19906 requires designing structures to contain spills resulting from inadvertent release of contaminants into the environment. Structural systems requiring active pollution operations should be avoided. Harmful environmental impacts should also be minimized during construction, transport, installation, and decommissioning. In particular, fluids and materials used for commissioning should be contained in double-barrier tanks to avoid harmful release into the environment. Structural design should facilitate environmental monitoring, which is addressed by the ISO 35103 standard. A protocol should be established for inspection, maintenance, and repair of tanks containing potentially polluting fluids and materials. Finally, dissolved oxygen content in cold waters is generally high, which enhances corrosion. Therefore, water content data should be collected locally to account for this factor in the choice of structural materials.

4 Innovations for practical applications

This category refers to design modifications applied to marine technology or equipment developed in other parts of the world for adaptation to the extreme Arctic conditions (low temperatures, high latitudes, polar night, remoteness, etc.). Environmental conditions affect hull structure, ship stability, machinery, communication and navigation systems, equipment functionality and efficiency, maintenance, emergency escape, and safety performance.

Following technological advances, the discovery of natural resources, and the climate warming-induced evolution of Arctic climatic conditions, human activities in the Arctic have recently diversified. Traditional activities of low-latitude oceans are appearing in the polar regions. This evolution requires new tools and protocol for production and social activity around the Arctic Ocean and provides an opportunity for marine engineers to create or adapt marine technology to the Arctic. For example, in low-latitude open waters, offshore oil and gas extraction and wind power generation are common, submarine cables on the seabed connect islands and continents, and aquaculture cages are installed in coastal areas. Such activities and equipment cannot be readily transferred to the Arctic without technological adaptation to polar waters. A common approach to achieve adaptation is “winterization”, which consists in ensuring that a structure is suitably prepared and operational in polar waters by designing operation protocols and choosing materials adapted to extreme conditions. Winterization ensures reliable functionality of systems and equipment and a safe working environment for resident personnel.

These innovations for practical application focus mainly on four categories of equipment: resource development, transport and communication, rescue, and scientific research and monitoring (discussed in Section 5). Oil and gas exploration, development, and engineering equipment includes drilling ships and platforms (Connelly and Brovkin, 2014), cold sea drilling equipment, gravity production platforms (Jackson et al., 2008), floating production platforms, and underwater production systems. Platforms or ships are designed with reinforced structures for enhanced resistance to ice. Examples are the Prirazlomnaya platform (Zhukov and Karlinsky, 2004) or the “Christophe de Margerie” class of liquefied natural gas carriers (Hannon, 2019). The ExxonMobil (United States) and Kvaerner (Norway) have submitted patent applications for ice-resistant drilling rigs that could endure winter without disfunction. In terms of transport, polar vessels include multipurpose ships, semisubmersible ships, oil tankers, liquefied natural gas ships, container ships, bulk carriers, ore carriers, and cruise ships. Finally, for life support and service to the resident population, rescue equipment includes icebreakers and lifeboats, while robotic equipment such as nimble robotic arms, immersive vision systems, and humanoid walking robots could reduce the need for continuous on-site human presence.

5 Innovations for observing information systems

The fourth category comprises innovations aimed at the expansion, diversification, and integration of Arctic-wide observation systems. This implies new scientific missions and activities in the Arctic to better characterize the changing environmental and ecological conditions, both in the Arctic system and at the global scale. Understanding dynamic modifications of the Arctic system requires comprehensive and consistent scientific observation data. Historically, Arctic observations were initiated to support weather forecasting, then surveys were conducted to accumulate measurements, for example on ocean currents, seabed topography, ice conditions, and biodiversity. Early observations of the Arctic Ocean, weather, and ice conditions were mostly acquired at fixed onshore observation stations or derived from ship-based measurements. Thus, the resulting datasets were spatially distinct and temporally discontinuous, because of the lack of standardization in local approaches and measurement protocols for different data sources and observation periods.

To characterize environmental variations and trends in the Arctic, technological innovations must address major issues: the scarcity of monitoring devices, the limited spatiotemporal coverage, and the low diversity and performance of currently-operational scientific equipment. Furthermore, access to data on different elements of the Arctic system (e.g., atmosphere, ocean, ice sheet) to support governance decisions should be maximized. Scarcity of ocean-based instruments (punctual measurements from isolated ships) and dataset "fragmentation" (no spatial and temporal continuity) are the main reasons for the limited information integration in existing Arctic observation systems.

Polar environmental observations should provide data with sufficient temporal sampling and spatial coverage, for example to support oil and gas exploration and development in specific regions of the Arctic Ocean. In terms of geophysical parameters, observations should target sea-ice, icebergs, waves, wind, and temperature. Necessary innovations should allow the characterization of ice thickness, and iceberg shape and oceanic track (King, 2018).

An early attempt at comprehensive observation acquisition is the International Arctic Buoy Programme (https://iabp.apl.uw.edu/). Extending since 1991 the Arctic Ocean Buoy Program initiated in 1979, the International Arctic Buoy Programme operates a network of automatic data buoys designed to monitor Arctic and global climate change, to support weather and sea-ice forecasting, and to provide a reference dataset for validation and assimilation of climate model output and satellite data.

Other important efforts have focused on using information technology to integrate data with differences in spatial scale, spatiotemporal coverage, observation method, and instrumentation. Merging measurements improves dataset accuracy and completeness, which is essential for comprehensive assessment of the distribution and trends of environmental geophysical parameters within the oceanic, polar, and Earth complex systems. For this purpose, data assimilation is a particularly useful method that should be supported by technological innovations.

Data assimilation combines numerical models and observations to characterize geophysical parameters and derive improved estimates of the true state of a system (Wikle and Berliner, 2007). Data assimilation has been extensively used for scientific studies of the atmosphere, ocean, and land surface. It uses observational data as input for a numerical model simulating a physical system (e.g., the atmospheric boundary layer). Observations provide input constraints to improve the model simulation performance; conversely, the model supplements the data (e.g., by gridded interpolation) to compensate their limited spatial and temporal coverage. For example, a large fraction of the Arctic Ocean is permanently covered by ice. Therefore, a data assimilation model should simulate dynamic ice–ocean interactions by including an ice–ocean coupling algorithm.

An example of multiple dataset integration in an assimilation system was the Integrative Data Assimilation for the Arctic System (IDAAS) (https://www.whoi.edu/science/PO/arcticgroup/projects/andrey_project2/indexAP.html), proposed in 2005 by a special US interagency research group in collaboration with international partners, the Study of Environmental Arctic Change (SEARCH) program (https://searcharcticscience.org/). Nominally, non-atmospheric components were planned for inclusion in IDAAS: oceanic, terrestrial geophysical and biogeochemical parameters, sea ice measurements, and human sociological data.

The proposal for IDAAS integrated the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) and the Semi-Implicit Ocean Model (SIOM) to assimilate sea ice, momentum, heat, and salt flux data within a four-dimensional variational assimilation algorithm. The proposed algorithm flowchart for this reanalysis system is presented in Figure 1.

Currently, collected Arctic data is "multidimensional". Besides an increased number of ground-based and ship-based instruments, modern observation platforms are satellite-borne, airborne, ice-based, or underwater. Figure 2 illustrates the types of devices that could be combined into an integrated system, for example the integrated Arctic Ocean Observing System (Dickson, 2006). With the increased portability and number of sensor types, the combined data volume has become considerable. For this reason, marine scientific equipment and observation processing systems should be designed to fulfill Arctic governance requirements. Furthermore, marine design innovations should consider the specific requirements for data assimilation and integration, for example by implementing mobile instruments that can accurately chart the water surface, the seabed, and specific subsurface depths involved in key scientific phenomena. Such instruments should be supported by optimized data collection with precise geolocation and temporal information. Simultaneously, efficient, secured, and reliable information transmission methods should be developed.

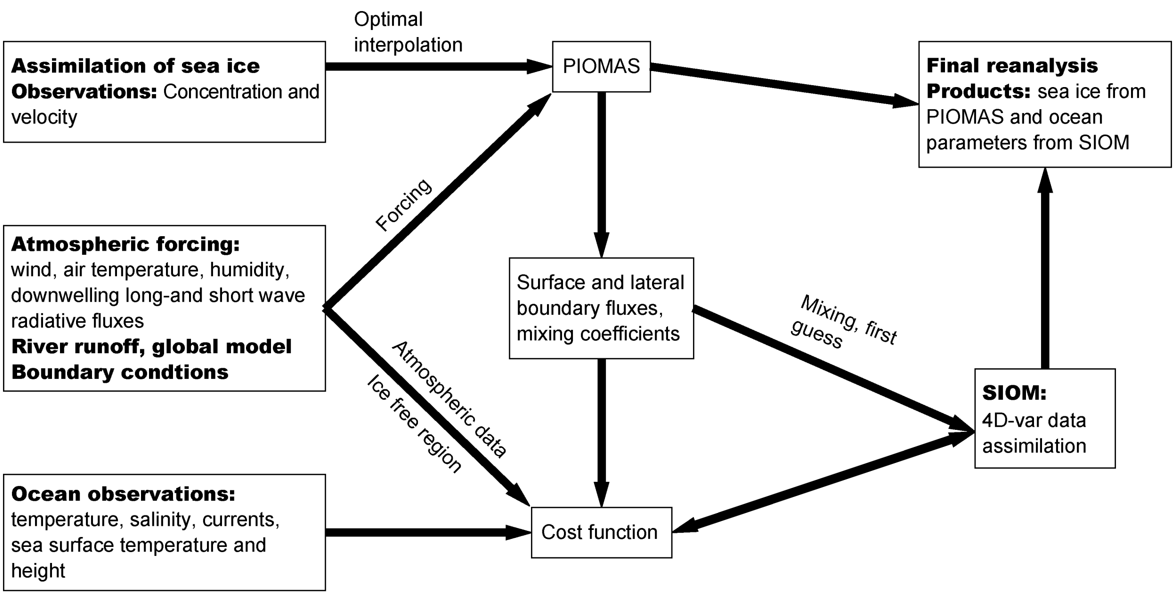

Figure 1 Proposed reanalysis system built around the PIOMAS and SIOM models (Proshutinsky et al., 2010).

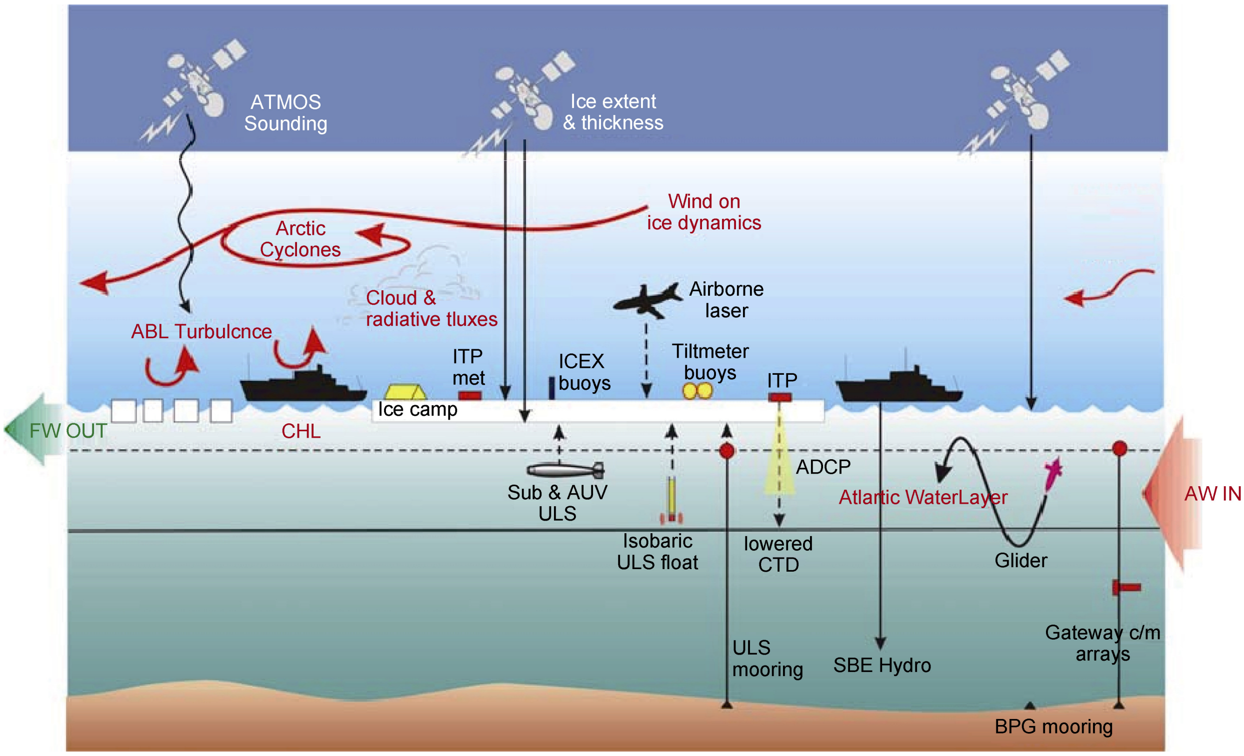

Figure 2 Schematic representation of vertically distributed observation components, from satellites to seabed sensors, in a proposed integrated Arctic Ocean Observing System (Dickson, 2006). ADCP, acoustic Doppler current profiler; AUV, autonomous underwater vehicle; BPG, bottom pressure gauges; CHL, cold halocline layer; CTD, conductivity, temperature, and depth; ITP, ice-tethered platforms; SBE, shelf–basin exchange; SSH, sea surface height; ULS, upward looking sonar.

Marine innovations for observing information systems include designing small equipment to operate on the seabed, underwater, at the sea surface, and on ice that can ensure information transmission and networking to complement shipborne monitoring devices, such as observation devices in specially designed unmanned remote-controlled vehicles operating underwater or at the surface. For data collection, data standards should be established for the next generation of information processing that will include data integration and assimilation by supporting models.

Marine equipment innovations should be systemic and compatible. Marine sensor-bearing vehicles also represent testing platforms for equipment release, machine installation, data collection, and safety assurance. Moreover, they should function as communication hubs to connect and transmit data. For example, a marine instrument could serve as a receiving station for satellites from GPS or for research satellites dedicated to sea or ice observations. Finally, innovations in marine equipment should comply with technical requirements for data collection and processing centers.

Figure 3 shows a second example of the diversity of marine equipment needed for an Arctic Observing System (Rigor, 2005): basin-scale autonomous underwater vehicles (AUVs) and their docking stations, moored profilers, gliders with water lasers, Argo floats, cabled seabed systems, upward-looking sonars, drifting buoys, ice-tethered platforms (ITPs), data shuttles, and underwater tomography receivers. To survey the polar subglacial marine environment, China has developed several types of unmanned underwater vehicles including the HaiJi remote operated vehicle, the TS-1000 AUV, and the Haiyi glider (Zeng et al., 2021).

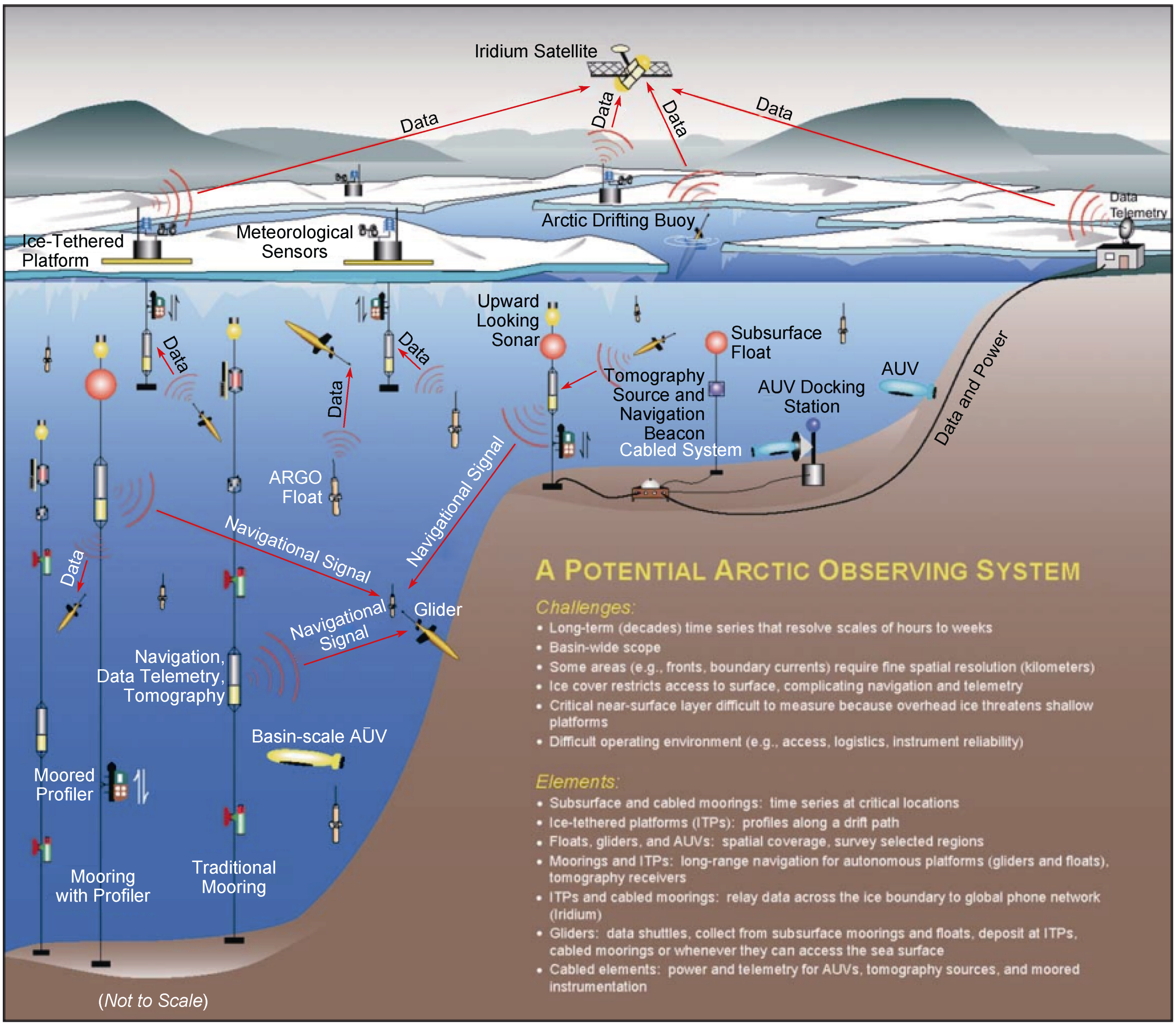

Figure 3 Schematic description of a proposed Arctic Observing System (Rigor, 2005).

6 International cooperation for Arctic marine innovation

Marine technological innovation in the Arctic requires applying new technologies to a highly unfavorable environment and cannot be achieved without extensive international cooperation. The international cooperation process that has taken place for the development of the Polar Code is a major international success in Arctic governance. It was developed collaboratively, under the guidance of successive IMO Secretary-Generals Koji Sekimizu (Japan, 2012–2015) and Kitack Lim (Korea, 2016–present), by Arctic countries (Canada, Denmark/Greenland, Finland, Norway, Russia, and the United States), East Asian maritime countries, and additional important shipping countries, before adoption in 2017.

The ISO 19906 standard was elaborated in 2010 and updated in 2019. Table 1 lists the WG8 member countries whose representatives drafted the standard (their affiliations in 2010 are also given). This list clearly illustrates that this standard benefited from the combined expertise of both Arctic and non-Arctic (China, France, Germany, Italy, Japan, Kazakhstan, the Netherlands, and the United Kingdom) countries. Significant experience on the characteristics and constraints of offshore structures was acquired in the 1980s, with ice loading measurements from offshore exploration platforms deployed in the Beaufort Sea (Sinsabvarodom et al., 2022). Results from more recent research projects, such as the European Union-funded measurements on Structures in Ice (STRICE) (https://cordis.europa.eu/project/id/EVG1-CT-2000-00024) projects or ice load measurements in the Bohai Sea in China, on the Confederation Bridge in Canada and in Japan (Blanchet et al., 2011), were incorporated into the ISO 19906 standard.

The Polar Code and the ISO 19906 standard provide a partial framework for Arctic governance by their important role for marine engineering and technology projects regulation. They also indicate possible directions for future marine technological innovation. Their implementation and adoption is a good example of constructive international cooperation and shows that the expertise, knowledge, and technology of countries outside the Arctic is useful for Arctic governance.

Table 1 WG8 member countries and their representatives (with affiliations) during development of the ISO 19906 standard (Blanchet et al., 2011)

Country	Representatives	Affiliation
Canada	D. Blanchet, K. Croasdale	BP, K. R. Croasdale and Associates
China	W. Dong, X. Yang	Chinese National Offshore Oil Corporation
Denmark/Greenland	O. Pedersen	Department of Petroleum, Bureau of Mines and Energy
Finland	M. Maattanen	Helsinki University of Technology
France	M. Vache	Doris Engineering
Germany	J. Schwarz, J. Berger	Cousultant, Impac Engineering
Italy	A. Baryshnikov	AgipKCO
Japan	K. Izumiyama, N. Nakazawa	NMRI, SEA System Engineering
Kazakhstan	K. Kaipyev, T. Svetlana, Y. Smagulov	JSC Board of Oil and Gas Industry, AgipKCO
Netherlands	F. Sliggers	Shell
Norway	O. T. Gudmestad, M. Morland	Statoil, Norsk Hydro
Russia	D. Mirzoev, M. Mansurov	VNIIGAZ
United Kingdom	G.A.N. Thomas, D. Clare	BP, Arup
United States	W. Spring, D. Hinnah, J. Hamilton	Bear Ice Techonology, MMS, ExxonMobil

China, Japan, and Republic of Korea are developed countries with a strong capacity for technological innovation, pursuing cooperation with Arctic countries to develop marine equipment in compliance with Arctic governance goals. Their expertise in information technology, shipbuilding, and cold-region and smart-technology port infrastructure construction, can benefit Arctic governance. A survey on technological innovations for sustainability in the Arctic led by Jong-Deog Kim, President of the Korea Maritime Institute, identified the following priority areas: ocean energy development and utilization; prediction and adaptation to ocean environmental changes; marine pollution mitigation; fundamental marine bioengineering; oceanographic observation and monitoring; development of ocean-specific equipment for exploration; port operation information system design; advanced maritime traffic automation and safety enhancement; fishery resources surveys; and aquaculture management. Most of these priority areas are related to marine technology, to which East Asian countries such as China, Japan, and Republic of Korea can contribute successfully in future.

7 Conclusions

In this work, we presented and discussed four categories of marine technology innovations for economic development and governance in the Arctic. Traditionally-oriented innovations mainly rely on previous experience to apply incremental improvements for safer and more reliable designs. Innovations for environmental protection are implemented to mitigate pollution of the Arctic air, water, and biome, with cost-control efforts to ensure engineering feasibility. Application innovations consist of adapting or upgrading existing lower-latitude marine structures, designed for less severe environments, to withstand the extreme conditions encountered in the Arctic. Technological innovations of the fourth category are intended for expansion and integration of available observation datasets in the Arctic, to investigate its climatic and environmental history and to predict future trends. The severe Arctic environment and limited availability of adapted technology have stimulated international cooperation. These collaborative efforts resulted in the successful development of regulations and governance protocols, such as the Polar Code and the ISO 19906 standard. Cooperation on Arctic marine innovation between East Asian and Arctic countries should be increased to promote sustainable development in that key region of the Earth system.

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