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Shared Arctic Variable Framework Links Local to Global Observing System Priorities and Requirements

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ABSTRACT. The geographic settings and interests of diverse groups of rights- and stakeholders figure prominently in the need for internationally coordinated Arctic observing systems. Global and regional observing systems exist to coordinate observations across sectors and national boundaries, leveraging limited resources into widely available observational data and information products. Observing system design and coordination approaches developed for more focused networks at mid- and low latitudes are not necessarily directly applicable in more complex Arctic settings. Requirements for the latter are more demanding because of a greater need for cross-disciplinary and cross-sectoral prioritization and refinement from the local to the pan-Arctic scale, in order to maximize the use of resources in challenging environmental settings. Consideration of Arctic Indigenous Peoples's observing priorities and needs has emerged as a core tenet of governance and coordination frameworks. We evaluate several different types of observing systems relative to the needs of the Arctic observing community and information users to identify the strengths and weaknesses of each framework. A typology of three approaches emerges from this assessment: "essential variable," "station model," and "central question." We define and assess, against the requirements of Arctic settings, the concept of shared Arctic variables (SAVs) emerging from the Arctic Observing Summit 2020 and prior work by the Sustaining Arctic Observing Networks Road Mapping Task Force. SAVs represent measurable phenomena or processes that are important enough to multiple communities and sectors to make the effort to coordinate observation efforts worthwhile. SAVs align with essential variables as defined, for example, by global observing frameworks, in that they guide coordinated observations across processes that are of interest to multiple sectors. SAVs are responsive to the information needs of Arctic Indigenous Peoples and draw on their capacity to codesign and comanage observing efforts. SAVs are also tailored to accommodate the logistical challenges of Arctic operations and address unique aspects of the Arctic environment, such as the central role of the cryosphere. Specific examples illustrate the flexibility of the SAV framework in reconciling different observational approaches and standards such that the strengths of global and regional observing programs can be adapted to the complex Arctic environment.

Key words: Arctic; observing; framework; essential variable; Shared Arctic Variable; Arctic Observing Summit

RÉSUMÉ. Les contextes géographiques et les intérêts de divers groupes de détenteurs de droits et de parties prenantes figurent au premier plan des besoins en systèmes d'observation de l'Arctique coordonnés à l'échelle internationale. Il existe des réseaux d'observation d'envergure mondiale et régionale visant à coordonner les observations en provenance de divers secteurs et de frontières nationales, s'appuyant sur des ressources limitées pour donner lieu à des données d'observation et à des produits d'information grandement accessibles. Les réseaux d'observation et les approches de coordination conçus pour des réseaux spécialisés desservant les latitudes allant de moyennes à faibles ne se transposent pas directement aux contextes plus complexes de l'Arctique. Dans le cas de l'Arctique, les exigences sont plus élevées en raison du plus grand besoin d'accorder de l'importance aux disciplines et aux secteurs variés ainsi qu'au raffinement de l'échelle, qui passe de locale à panarctique, afin de maximiser l'utilisation des ressources dans des contextes environnementaux difficiles. La considération des besoins et des priorités d'observation des peuples autochtones de l'Arctique constitue un des principaux principes des cadres de gouvernance et de coordination. Nous évaluons plusieurs types différents de réseaux d'observation à la lumière des besoins de la communauté d'observation de l'Arctique et des utilisateurs d'information afin de cerner les forces et les faiblesses de chaque cadre de référence. Cette évaluation a permis de produire une typologie de trois approches : la « variable essentielle », le « modèle de station » et la « question centrale ». Nous définissons et évaluons, en fonction des exigences des contextes de l'Arctique, le concept des variables partagées de l'Arctique (SAV) qui est ressorti du sommet d'observation de l'Arctique de 2020 et de travaux antérieurs réalisés par le groupe de travail des réseaux Sustaining Arctic Observing Networks Road Mapping Task Force. Les SAV représentent des processus ou des phénomènes mesurables suffisamment importants

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aux yeux de communautés et de secteurs divers pour que la coordination des efforts d'observation en vaille la peine. Les SAV concordent avec les variables essentielles comme définies, par exemple, par les cadres d'observation mondiaux, en ce sens qu'elles guident les observations coordonnées relevant de processus qui revêtent de l'intérêt pour de multiples secteurs. Les SAV accordent de l'importance aux besoins en information des peuples autochtones de l'Arctique et font appel à leurs capacités à concevoir et à gérer les efforts d'observation en collaboration. Par ailleurs, les SAV sont conçues pour tenir compte des défis logistiques des opérations dans l'Arctique et tiennent compte d'aspects uniques de l'environnement arctique, comme le rôle central de la cryosphère. Certains exemples illustrent la souplesse du cadre des SAV pour réconcilier diverses approches et normes d'observation, de sorte que les points forts des programmes d'observation mondiaux et régionaux puissent être adaptés à l'environnement complexe de l'Arctique.

Mots clés : Arctique; observation; cadre de référence; variable essentielle, variable partagée de l'Arctique; sommet d'observation de l'Arctique

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INTRODUCTION AND BACKGROUND

A truly coordinated Arctic observing system that links priorities identified at the local community scale all the way up to requirements defined in the context of global observing systems would make for better observations, more efficient use of resources, increased coverage, and expanded cooperation between the observing community and information users from different sectors (including public, private, non-profit, and tribal/first nations). As it stands though, the Arctic observing environment comprises a mixture of small research projects, larger national operational efforts, coordinated discipline-specific programs, and private-sector and community observations. Background data compiled for the 3rd Arctic Science Ministerial in 2021 (ASM3, 2021) highlight both progress and shortcomings with respect to coordinated observations in the Arctic. Observing efforts often have conflicting requirements. For example, the biological science community might like to see fisheries data shared, while private companies have economic interests in restricting access to it (Couture et al., 2018); and observational design in support of unsustainable resource management practices might function to the exclusion of observations needed for alternate, more sustainable approaches. Observing efforts can also largely exclude Indigenous communities that could benefit from the research investment in the region. This article describes shared Arctic variables (SAVs), an organizational structure for coordinating observing efforts across areas of shared interest, and how SAVs are derived from, and relate to, other observation coordination frameworks.

A coordinated Arctic observing system, or system of systems, would need to meet a variety of rights- and stakeholder needs and have space for contributions from the scientific community, along with operational agencies from many nations, the private sector, and, importantly, the Indigenous Peoples of the Arctic. Such a complex system cannot arise organically on its own, but requires collaborative frameworks and guidance, along with coordinated implementation, to meet observing needs from the local level (e.g., marine mammal population and health monitoring) to the global level (e.g., meteorological data for weather forecasting).

The SAV concept described here is the result of an extended discourse by Sustaining Arctic Observing Networks (SAON, https://www.arcticobserving.org) and participants in the biennial Arctic Observing Summit meetings (AOS, arcticobservingsummit.org). Each AOS serves as an opportunity for the Arctic observing community to come together, exchange ideas, and coordinate joint action; this community includes, but is not limited to, research scientists, operational observing system representatives, community-based networks, Indigenous Peoples organizations, private-sector data providers and users, data managers, and others. Over several years of the AOS, widespread agreement emerged that SAON should take a more active role in developing a framework for coordination of Arctic observations. In 2018 the Arctic Science Ministerial (ASM3, 2021) likewise tasked SAON with this role (ASM2, 2019). Around the same time, SAON developed the ROADS (Roadmap for Arctic Observing and Data Systems) Task Force (Starkweather et al., 2021), which, in 2019, initially proposed an essential variable framework called "essential Arctic variables" (Starkweather et al., 2019). Several working groups at the 2020 AOS discussed the proposed framework (AOS, 2020); Working Group 1 (WG1: System Design, Optimization, and Implementation) in particular explored what a successful observing system framework for the Arctic would need to achieve. In writing this paper, the authors, who were all involved in the leadership of WG1 at the 2020 AOS, started from summit deliberations.

This contribution builds on the recommendations of the SAON ROADS Task Force (Starkweather et al., 2021) and deliberations at the 2020 AOS (AOS, 2020) and prior summits; it investigates existing models for a coordinated observing system, identifying practices that are most suitable for adoption into a coordinated framework of Arctic observing activities and systems. After a brief review of the relevant background, we explore key overarching requirements common to many sustained Arctic observing efforts. These observing-system attributes are analyzed in more detail for a set of representative examples of global and regional Arctic observing systems. Building on this work and outcomes of the 2020 AOS, we explore essential aspects of the implementation of a coordinated observing systems framework. By drawing on the 2020 AOS and the relevant strengths of extant observing systems, we define the concept of SAVs and discuss implications for the establishment of coordinated Arctic observing systems.

Global Observing Systems

Global observing systems provide international frameworks for prioritizing, coordinating, and implementing observations around areas of common interest and are backed by a structure that lends such efforts credibility and authority. A well developed observing framework facilitates national, local community, or private-sector observing efforts to address societal needs, while reducing replication of efforts because data are of a known standard, freely available, and complementary in spatial-temporal coverage (e.g., Lindstrom et al., 2012).

Approaches to global observing systems vary significantly in details, but the predominant mechanism is based on establishment of a roster of jointly identified essential variables: a centrally selected set of most important variables for which observing requirements are subsequently defined. By subscribing to this essential variable approach, the observing community implements measurements of these variables according to predefined standards, followed by archiving in a coordinated and accessible manner. Observing systems can vary regarding who carries out these measurements and with what level of commitment. For the larger observing systems, contributions are typically managed in a system-of-systems approach, with national and even international observing networks addressing elements of the observing goals. For example, the primary contributors to the Global Climate Observing System (GCOS) are major agency programs like Copernicus, the European Union's Earth Observation Programme (Le Traon et al., 2019), which itself consists of a large number of observing programs. Similarly, the components of the World Meteorological Organization's (WMO) Global Observing System are coordinated by the national meteorological and hydrological services of WMO members, as well as by other national and international agencies, such as space agencies and private entities.

These systems operate in a global, hierarchical framework in which expert groups identify the most important (essential) variables and then define the observing requirements. By necessity, global observing systems assess relevance of variables globally. For geographic regions or communities that may have different information[al] needs or frameworks within which to assess relevance, that "one-size-fits-all" approach typically does not meet local needs. A tailored, regional solution can be more responsive to local concerns.

Specifically, a bottom-up approach, where information users, rather than scientists or information providers, lead the definition and requirements capture process, would be more likely to meet the needs of the people and communities that would use the observations collected. Global observing frameworks are mindful of user needs, though they tend to align with global assessment and treaty systems as well as existing connections to operational intergovernmental bodies (e.g., the Joint Technical Commission for Oceanography and Marine Meteorology for ocean observing), as apparent from syntheses such as Muller-Karger et al. (2018) for essential ocean and biodiversity variables or Eicken et al. (2021) for environmental monitoring more broadly. This results in an emphasis on top-down, globally defined observables, shifting attention away from local-scale user priorities. This context is key to the concept of SAVs, which focuses on observations that combine local priorities and benefits (in particular, those of Indigenous communities); regionally defined science and decision-support needs; and global essential variable priorities (Starkweather et al., 2021).

Observing in the Arctic

In the Arctic, particular geographic, climate, and logistical difficulties in carrying out observing activities create demand for coordinated efforts. In global observing systems, the Arctic is notably undersampled with in situ measurements (e.g., Riser et al., 2016; Wohner et al., 2021), resulting in sparse data to represent a region experiencing rapid climate change.

The Arctic Ocean is difficult to access, with a limited number of icebreakers able to safely operate through much of the year (Drewniak et al., 2018). Observing resources deployed on sea ice drift with the ice and are often lost after a season (IABP, 2020). Climate change is driving a trend towards increasingly seasonal ice cover (Perovich, 2011) and higher drift speeds (Spreen et al., 2011), making it more difficult to maintain observing platforms on the ice. Sea ice cover complicates the use of ocean observing instruments, resulting in an undersampled Arctic Ocean (e.g., Lee et al., 2019; Argo, 2000).

Weather stations and balloon soundings are similarly sparse in the Arctic (Durre et al., 2006), again largely due to access limitations. Limited road access, combined with sporadic ship access to coastal villages, means that many locations are reliant on small aircraft. Severe weather, cold temperatures, and extended periods of darkness make maintaining instruments challenging. Maintaining an Arctic research station on land is therefore an expensive proposition, and then there is still the entire Arctic Ocean, with few observations outside of drifting buoys and the occasional scientific expedition (e.g., Multi-Disciplinary Drifting Observatory for the Study of Arctic Climate [MOSAiC], https://mosaic-expedition.org/).

Terrestrial in situ observing networks are similarly challenged, with the Arctic underrepresented at the global scale in terms of long-term ecological observing efforts (Wohner et al., 2021). Equally problematic are recent findings showing that Arctic field studies and sustained observations are geographically biased towards the immediate vicinity of Toolik Lake in Alaska and Abisko in northern Sweden (Metcalfe et al., 2018). However, in the Arctic, community-based or bottom-up observing or monitoring efforts (such as the Yukon River Inter-tribal Watershed Council Water Stewardship Program) are more common relative to top-down, large-scale observing efforts (such as the United Nations Global Environment Monitoring System for freshwater) than in other regions of the globe (based on a review of the global literature by Eicken et al., 2021). This latter finding points to the great potential of Arctic Indigenous community-driven observing programs, provided that capacity and systemic challenges can be overcome (Danielsen et al., 2021; Eicken et al., 2021).

Darkness in winter and frequent cloud cover in summer likewise limit optical remote sensing observations (Comiso, 1991), while microwave remote sensing suffers from large uncertainties due to the paucity of in situ calibration data and the lack of polar-specific retrieval algorithms (Brodzik et al., 2018). Altogether, these limitations limit the use of satellite observations to fill in the large gaps left by in situ observations. At the same time, the geometry of polar orbits means that many satellite-based sensors pass over a given location in the Arctic far more often than at lower latitudes, providing an extraordinary amount of data that is currently not exploited.

Indigenous communities thrive in the region. Inuit, Aleut, Athabascan, Gwich'in, Saami, and other peoples have lived in the Arctic for millennia, relying on their own observations and knowledge of the surrounding environment. Indigenous knowledge integrates experiences, observations, and lessons over generations into a way of thinking about biological, physical, and cultural systems (ICC, 2020). Scientific and operational observing efforts have largely ignored these knowledge systems (Johnson et al., 2015), and observing approaches designed without significant input from Indigenous communities struggle to meet the information needs of those communities (e.g., Eicken, 2013; Danielsen et al., 2021). Co-production of knowledge (CPK) is the process of developing new knowledge through the equitable interaction of different knowledge systems (e.g., scientific and Indigenous ways of knowing) in a context-based and goal-oriented partnership (Rudolf, 2021). An Arctic observing system that meets the needs of Indigenous communities in the region and builds on CPK principles requires equitable involvement of Indigenous participants.

State of Arctic Observing Systems

There is a clear need for sustained, coordinated Arctic observations that track subseasonal to multidecadal change, advance understanding of Arctic social-environmental systems, and inform predictions of, and responses to, rapid Arctic change across a range of scales and sectors. This need has been articulated in broader assessments that have focused on societal benefits (STPI-IDA and SAON, 2017; Strahlendorff et al., 2019), economic benefits (Dobricic et al., 2018), Indigenous perspectives (ICC-AK, 2015), and research priorities (Lee et al., 2015, 2019; Tjernström et al., 2019; Zakharova et al., 2019). The SAON initiative, the AOSs (Murray et al., 2018), and the Arctic Science Ministerials (ASM2, 2019; ASM3, 2021) have furthermore provided a high-level inventory of the range of observing activities currently underway in the Arctic.

A number of research projects and coordination efforts have begun to address the question of how to achieve convergence or develop synergies among the different types of observing activities and approaches. Projects emerging out of the International Arctic Science Committee (IASC) working groups, such as MOSAiC, have mostly been driven by scientific research questions to help improve understanding of processes and linkages. The European Union's Horizon 2020 program has supported both observing system assessment and design-focused work, such as the INTAROS project (Integrated Arctic Observation System; see in particular the observing system assessment by Tjernström et al., 2019), as well as infrastructure-focused efforts, such as an Arctic Data Portal (https://portal.emodnet-physics.eu/arctic-data-portal/). The latter portal was established in 2020 by a group of organizations that includes the European Marine Observation and Data Network (EMODnet) and the In Situ Thematic Centre (INS TAC). A Polar Observing Assets Working Group (https://www.polarobservingassets.org/) focuses on the coordination of observing metadata.

From this work emerges a picture of the current state of observing systems, comprised of an assortment of sustained and short-term observations covering a range of spatial and temporal scales, operators and data users, and observing infrastructure. Programs at the pan-Arctic scale are often focused on a comparatively narrow set of variables, with observations administered by government agencies as part of international observing frameworks. The WMO's Global Atmosphere Watch (GAW) and Global Cryosphere Watch (GCW) are examples of such efforts. GAW maintains a well-established station network with highly interoperable observations typically conducted by the national meteorological services. GCW is an evolving observation program with the list of core variables and requirements growing over the past years (Key et al., 2015; https://globalcryospherewatch.org/). While somewhat broader in terms of processes and variables covered, the Circumpolar Biodiversity Monitoring Programme (Gill and Zöckler, 2008) is also mostly supported through government agencies under the umbrella of the Arctic Council's Conservation of Arctic Flora and Fauna program.

At the regional and local scales, observing programs are typically more diverse in terms of approaches and variables measured, since the drivers for observations are defined in response to broader constituencies, such as in regional ocean observing systems (Lee et al., 2019) or community-driven observations (Johnson et al., 2015; Eicken et al., 2021). Similarly, observing systems anchored by local observing infrastructure, such as those associated with field stations or laboratories, typically encompass a broad range of observations within a specific geographic locale. The Svalbard Integrated Arctic Earth Observing System (SIOS, 2020) is a prime example of a location-based observing system developed in a region with particular logistical challenges. SIOS coordinates and facilitates sharing of observations from Svalbard, including in situ and linked remote sensing data. A centralized SIOS Knowledge Center is staffed to provide support for SIOS, including logistics management to coordinate observing activities and to facilitate communication among SIOS working groups and the research community. Data management policies are guided by the SIOS Data Management System Working Group, which promotes open access to data, facilitates adoption and implementation of data standards, and engages with partners across disciplines and geographic scales to facilitate cost-effective and sustainable data management practices (SIOS, 2020). Funding from the Research Council of Norway provides financial support for these coordination and implementation efforts.

Another regionally focused observing effort is the proposed Greenland Ice Sheet Ocean Observing System (GrIOOS). Research stations that would be part of this observing system would include a minimum standard of instrumentation (Straneo et al., 2018, 2019) in order to collect an interoperable set of measurements that would span several scientific disciplines.

It is worth noting that SIOS and GrIOOS are focused on understanding key components of the climate system, with an emphasis on physical science observations. As a consequence, implementation of core observing data to be collected and shared tends to be driven by the scientific research community, with emphasis on global efforts, where standard observing data needs and observing protocols may already be established. However, to capture a complete picture of the Arctic physical, ecological, and socio-economic system and optimize benefits from the local to the pan-Arctic scale, community-based observations carried out by Arctic Indigenous Peoples and communities need to interface with in situ and remote sensing observing systems. The need for such an interface is addressed below, as we introduce the concept of shared Arctic variables, which is complementary to, but distinct from the different types of essential variable or observational approaches captured in the work briefly highlighted in the preceding paragraphs.

These different types of sustained observations have mostly evolved independently of one another, resulting in the current patchwork of efforts, as illustrated in an inventory of observing sites compiled at the national level by the US Arctic Observing Viewer team (arcticobservingviewer.org). Inventories of observing assets (e.g., Manley et al., 2022; Polardex, https://polardex.org), data (held by data repositories), and observing systems (see INTAROS products, https://intaros.nersc.no) are key to an organized observing system, but they offer little guidance for next steps. The potential benefits from greater coordination of independently designed and implemented observing efforts are substantial, and some regional programs, such as the multinational Distributed Biological Observatory in the Pacific Arctic sector (Grebmeier et al., 2019), have identified and explored ways to close this gap. At the pan-Arctic scale, SAON and its Roadmap for Arctic Observing and Data Systems are poised to implement a cross-disciplinary approach that seeks to add value to observations across all scales, societal benefit areas, and knowledge systems (Starkweather et al., 2021). This approach will address a core problem central to the ROADS process, namely, the development of a framework of core variables that address societal benefit areas and information needs, and that are specific enough to guide observing system requirements and engineering design. In the subsequent sections we explore different approaches taken by global and regional observing systems in defining and linking essential variable observing frameworks, with an in-depth examination of several relevant case studies. Building on this review and drawing on AOS 2020 deliberations, we present a shared Arctic variable framework to serve the needs of the ROADS process in the Arctic.

ARCTIC OBSERVING SYSTEM REQUIREMENTS

For an organized, cross-sectoral, international observing framework to succeed in the Arctic, it must meet the needs of the whole Arctic observing community (including data producers and users) and be able to operate in Arctic conditions with limited resources. Complementing the in-depth discussion by Starkweather et al. (2021) and the SAON ROADS Task Force, we provide a brief perspective based on discussions at the 2020 Arctic Observing Summit, which highlighted five interrelated requirements for the system. Many of these requirements have been identified in the ROADS process (Starkweather et al., 2021). For the purposes of this discussion, the proposed system is referred to as the Arctic observing framework (AOF) in order to differentiate it (at least by acronym) from the Arctic Observing Summit (AOS).

1. Addresses information needs across many sectors/communities: For an AOF to be valued by the whole Arctic community, it needs to serve, to some degree, the information needs of all constituents. A framework based on information-user requirements will best align observing resources with the societal benefits derived from that information.
2. Incorporates contributions from many sectors/communities: The AOF must be flexible enough to incorporate observations from a variety of sources—researchers, operational agencies, Indigenous communities, and the private sector—with varying levels of formal training, experience, and equipment. Such integration and coordination of observing efforts

across the broader Arctic observing community is the core goal of the ROADS process (Starkweather et al., 2021), which has put forward the concept of expert panels, reflecting the different constituencies, to accomplish common goals.

3. Provides flexible requirements for technology: The AOF must have mechanisms for integration of new sensing platforms and sensor designs into measurement standards, as it is critical for ongoing development of Arctic observing to encourage new research in this area, including approaches that address challenges like limited internet access and other communication hurdles.
4. Leverages limited resources: In order to optimize observing resources in the face of the high costs of making observations, there should be few and low barriers to contributions. Local Arctic communities and Indigenous experts can provide critical capacity to maintain long-term observations and overcome logistics challenges, as demonstrated during the COVID-19 pandemic, when Bering Straits communities informed resource managers on the level of marine mammal and seabird strandings in the summer of 2020, and partnerships with local organizations also supported the collection of observations to track the of movements of ice floes (Prewitt et al., 2020).
5. Recognizes the interconnectedness of Arctic observables: Contributions by the AOS Food Security Working Group have emphasized the degree to which disparate parts of the Arctic geophysical-biological-social system are interconnected, drawing on Indigenous knowledge with its inherently holistic worldview in which no component exists in isolation (ICC, 2020). An effective AOF must facilitate linking observations across traditional scientific boundaries.

PERSPECTIVES ON SELECTED OBSERVING SYSTEM APPROACHES

Having briefly reviewed the background and attributes of Arctic observing system implementation, we now examine key aspects of established observing networks, as relevant to the Arctic and, in particular, as applicable to the SAON ROADS process (Starkweather et al., 2021). We consider five global and two regional observing systems that coordinate observing efforts directly, rather than making recommendations for scientific priority areas in general. Collectively, these systems use different approaches for organizing and coordinating observations, including organizing around essential variables, a station model, and central questions. Each system is briefly described below, followed by a table that summarizes each type of system with regards to the needs of an Arctic system, as defined in the previous section. These observing frameworks were developed for specific purposes other than as an Arctic observing system of systems, and each model exhibits strengths and weaknesses with respect to this purpose.

Survey of Selected Arctic-relevant Observing Systems

In the context of our review, we consider the following global systems: Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), Global Cryosphere Watch (GCW), Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) Initiative, and Group on Earth Observations Biodiversity Observation Network (GEO BON). Regional systems considered include SIOS and GrIOOS. These were selected as the most relevant different framework structures for coordinating observing efforts at the global scale and two additional structures designed specifically for the Arctic context. There are other observing systems that use each of the three framework structures described in the following sections, but including additional examples did not provide deeper insight into how the structure might meet the needs of an AOF.

GCOS: Co-established in 1992 by the WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, UNEP, and the International Council for Science with an aim to coordinate and make available observations and information needed to address climate-related issues, GCOS remains one of the most comprehensive global climate observing initiatives. GCOS is linked to other primary observing systems, including the GOOS and GCW, reviewed below. Principal components of the system are essential climate variables (ECVs), with particular definitions and measurement standards (Bojinski et al., 2014). ECV's include atmosphere, terrestrial, and ocean observing parameters selected to characterize Earth's climate and defined by expert panels at a joint meeting; requirements for some variables (but not all) are coordinated (GCOS, 2010). Contributed observations are gathered through major institutions, agencies, and national programs, with cooperation mechanisms supporting efforts in under-resourced regions (Plummer et al., 2017). The global network of large observing efforts creates a worldwide observing system with reliable observations of essential climate variables, but has few opportunities for grassroots-level contributions.

GOOS: GOOS is a sustained, collaborative system of ocean observations encompassing in situ networks, satellite systems, governments, UN agencies, and individual scientists. GOOS is administered by the IOC and, together with the GCOS and others, feeds into the Global Earth Observation System of Systems (GEOSS). GOOS utilizes the framework for ocean observing based on essential ocean variables (EOVs). EOVs are selected by expert panels, with definitions and measurement standards (Lindstrom et al., 2012) based on the science-driven requirements resulting from societal issues. Expert panels operate across disciplinary boundaries to consider coordination between variables. Observations come primarily from regional operational agencies and oceanographic institutions (Cai et al., 2015), with some contributing from vessels of opportunity (commercial and research vessels) operating in the region. Some variable standards rely on instrumentation, with limited variability (e.g., Argo floats: Argo, 2000; Lindstrom et al., 2012), but the framework includes a pilot project process for integrating new technologies (Moltmann et al., 2019). The GOOS Regional Alliances offer an entry point into this network for less mature observing programs (Moltmann et al., 2019).

GCW: GCW, established by the WMO, is an international observing system developed for supporting key cryospheric in-situ and remote sensing observations. GCW also feeds data into the GEOSS as a component of the WMO Integrated Global Observing System. GCW is focused on providing synthesis information regarding the cryosphere (GCW, 2015) and supports this effort through a network of surface observation stations called "CryoNet." CryoNet sites are maintained by scientific agencies and participating research programs (Key et al., 2015) and add up to a larger network with more coverage than any one contributing program or nationality could accomplish on their own (Fierz et al., 2018). CryoNet sites pair cryospheric observations with meteorological and other types of measurements for investigation of the coupled systems (GCW, 2018).

GEOGLAM: GEOGLAM aims to increase market transparency and improve food security by producing and disseminating relevant, timely, and actionable information on agricultural conditions. The GEOGLAM framework resulted from the Group of Twenty (G20) Agriculture Ministers meeting during the French G20 presidency in 2011. GEOGLAM produces regular reports on conditions of crops around the world; data are gathered and synthesized for use in generating these reports (Jarvis, 2020; Becker-Reshef et al., 2018). Data contributions include on-the-ground reporting from networks within countries and the larger-scale Earth observation (satellite, etc.) communities, with local reports supplementing remote sensing observations. A hierarchical information gathering and report generating process yields regular analysis from around the world despite uneven sensor coverage (Jarvis, 2020). The operational research and development branch of GEOGLAM develops new methods and analysis tools (Jarvis, 2020), ensuring a regular process for integrating new observing technologies. The interconnectedness of Earth system components is integral to the food-security and crop-health focus.

GEO BON: GEO BON is a global biodiversity observation network that contributes to effective management policies for the world's biodiversity and ecosystem services. GEO BON facilitates national biodiversity observing networks (BONS) through use of essential biodiversity variables (EBVs) and produces higher-level synthesis products (Pereira et al., 2013). GEO BON is a part of Group on Earth Observations (GEO) and ultimately feeds into GEOSS. The data products are aimed at the scientific community and decision makers (usually national governments). While the products are not structured around societal benefits, the Aichi Targets list biodiversity benefits to humanity (SCBD, 2010; Marques et al., 2014). Data contributions to GEO BON come through regional/national BONs (SCBD, 2010), of which there are currently at least 25, representing most of the Earth's major biomes. The "BON in a Box" approach provides a set of EBVs and measurement protocols with feasibility notes developed from successful regional systems (GEO BON, 2008); many core measurements are low-tech (e.g., species counts) (Pereira et al., 2013), which makes them relatively low-cost to set up.

SIOS: SIOS is a regional observing system for long-term measurements in and around Svalbard. Core data products are approved by a steering group based on length of observing period commitment and relevance to science priorities (SIOS, 2016). The Science Optimization Advisory Group comprises a range of national and international academic and research institutions and agencies, plus NGOs, that advise SIOS on scientific and societal relevance and the overall strategic goals of the observing system. Observations are produced by scientific activities (SIOS, 2016) but currently lack systemic efforts to coordinate between variables. Generally, the observations address the needs of the scientific community, with most of these ultimately motivated by understanding climate (van den Heuvel et al., 2019). Data sharing and observing standards reduce duplication of efforts in the high-cost Svalbard region (SIOS, 2016).

GrIOOS: GrIOOS is an initiative that seeks to establish a network of sites in Greenland with a common set of observed variables, measurement standards, and data protocols (Straneo et al., 2019). The system as a whole is motivated by understanding climate change (Straneo et al., 2019), but some potential sites of this network may also address local Greenlandic societal needs. Each station would be outfitted with similar instrumentation (the recommended set of instruments costing up to US$700,000; Straneo et al., 2018). This would facilitate directly intercomparable observations of the integrated geophysical and meteorological system across Greenland (Table 1).

Observing System Typologies

Among the global and regional observing systems considered here, three types of approaches to coordinating observing efforts have emerged and are discussed in more detail in the following subsections: "essential variables," where core variables are selected by expert groups and observers contribute to particular variables, "station model," where a standard set of observations/instrumentation is developed by an expert group for all participating locations, and "central questions," where observing efforts are coordinated at a regional level to address larger overarching questions without an emphasis on data sharing/interoperability (Table 1). These typologies emerged from a combination of documented duplication of approach (in the case of essential variable types) and critical reading of organizational documents for other observing system frameworks (for station model and central question approaches).

TABLE 1. Evaluation of three observing frameworks by the five identified Arctic system requirements.

Observing framework	Variables interconnect?	Leverages limited resources?	Flexible regarding technology?	Accepts contributions from many sectors?	Addresses needs of many sectors?	Example systems
Essential variable	Defined individually; requirements can be coordinated with effort	Depends on specific requirement; all observers meeting observation requirements can contribute	Depends on how observing requirements are set	Most observations come from major observing institutions/agencies, but model open to observations from any source	Variables selected by expert groups that could represent needs of many sectors. Defining observing requirements that satisfy all stakeholders is a challenge	GCOS; GOOS; GEO BON; SIOS
Station model	Designed to coordinate measurement of interconnected variables	May lack flexibility if site requirements too stringent	Most likely to have specific technology requirements	Stations built by research institutions or national observing programs, but could be contributed to by anyone, given resources	Stations designed to maximize research utility, rather than cross-sectoral needs	GCW-CryoNet; GrIOOS
Central question	Designed for complex systems where considering linked processes is critical	Delegated working groups can focus on most relevant observing resources in their area	Flexible observation requirements allow for easy adoption of different approaches	Delegates/working groups draw from many sources, including across sector boundaries, to compile analyses	Focus on particular areas of concern or sectors (e.g., agriculture)	GEOGLAM; GCW

Essential Variables Type: Essential variables are a prominent feature of the largest global observing networks, where a set of variables and observing standards are developed by groups of experts, and then contributing agencies/institutions make the measurements and distribute the data according to the data standards required by the observing system, as illustrated in Figure 1. The essential variables approach has been used successfully by GCOS (Bojinski et al., 2014) and GOOS (Tanhua et al., 2019). Essential variables common to GCOS and GOOS include, for example, sea surface temperature and salinity, surface currents, and sea ice. Note that many of these variables actually represent bundles of observable quantities subsumed under a heading describing a broader set of phenomena or processes. This is illustrated by the use, by GCOS and GOOS, of sea ice as an essential climate or ocean variable. As detailed by Lavergne et al. (2022), this single variable is actually a set of seven distinct observable quantities, including, for example, sea ice concentration, thickness, and snow depth. As we will discuss further below, the SAV framework also considers sets of observable quantities with the additional requirement that these quantities are tied to a broader phenomenon or process of relevance to intersecting, shared interests.

The essential variables model provides a flexible, clear mechanism for additional contributions. Potential new observers can look up the measurement standards for a particular variable (e.g., the GCOS sea level essential variable requirements are available at GCOS, 2016), and if they can meet those standards with a validated measurement protocol, they can contribute observations. This approach can be replicated to expand as additional variables become observable through technological development, or as a need for the information arises. It can, however, be difficult to integrate new technologies, as essential variables may have measurement standards developed specifically for established methods.

That said, defining the standards is an onerous process and requires stating that some variables are more important (essential) than others. When everyone working on the problem is in the same discipline (e.g., oceans or climate), that is challenging enough (Bojinski et al., 2014), but the challenge is magnified when contributing communities extend across a broad range of disciplines and sectors and may share fewer common interests.

Station Model Type: The second major type of observing system is organized around station models, as seen with GCW's CryoNet sites and the proposed GrIOOS. In this framework, the basic organizational structure of the observing system is the observing site, which could be anything from a major research facility to a single measurement platform (e.g., automated weather stations) to a designated plot (e.g., for ecological monitoring). Figure 2 illustrates this process. Some set of measurements is established by an interdisciplinary expert committee as a generic observation station, and participating nations, institutions, and research facilities are tasked with building

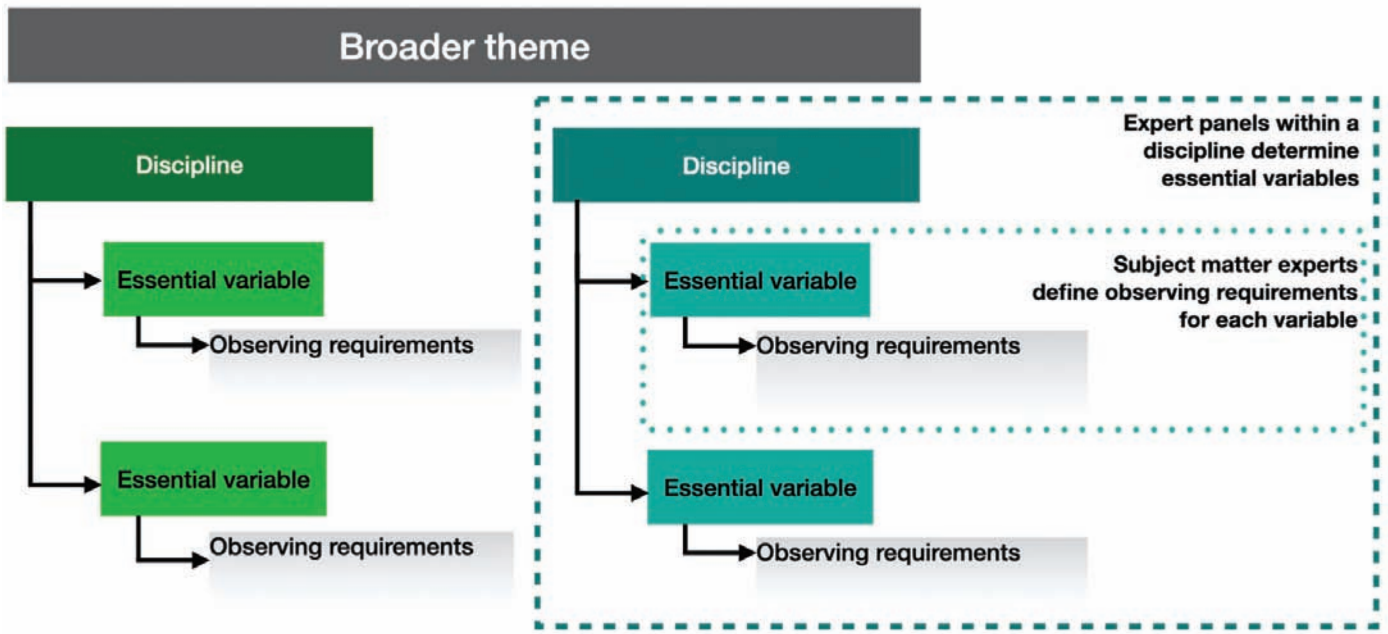

FIG. 1. Generic type of essential variable systems for coordinating observations. Within each broader discipline, essential variables are selected by expert panels, then observing requirements for those essential variables are developed by subject matter experts.

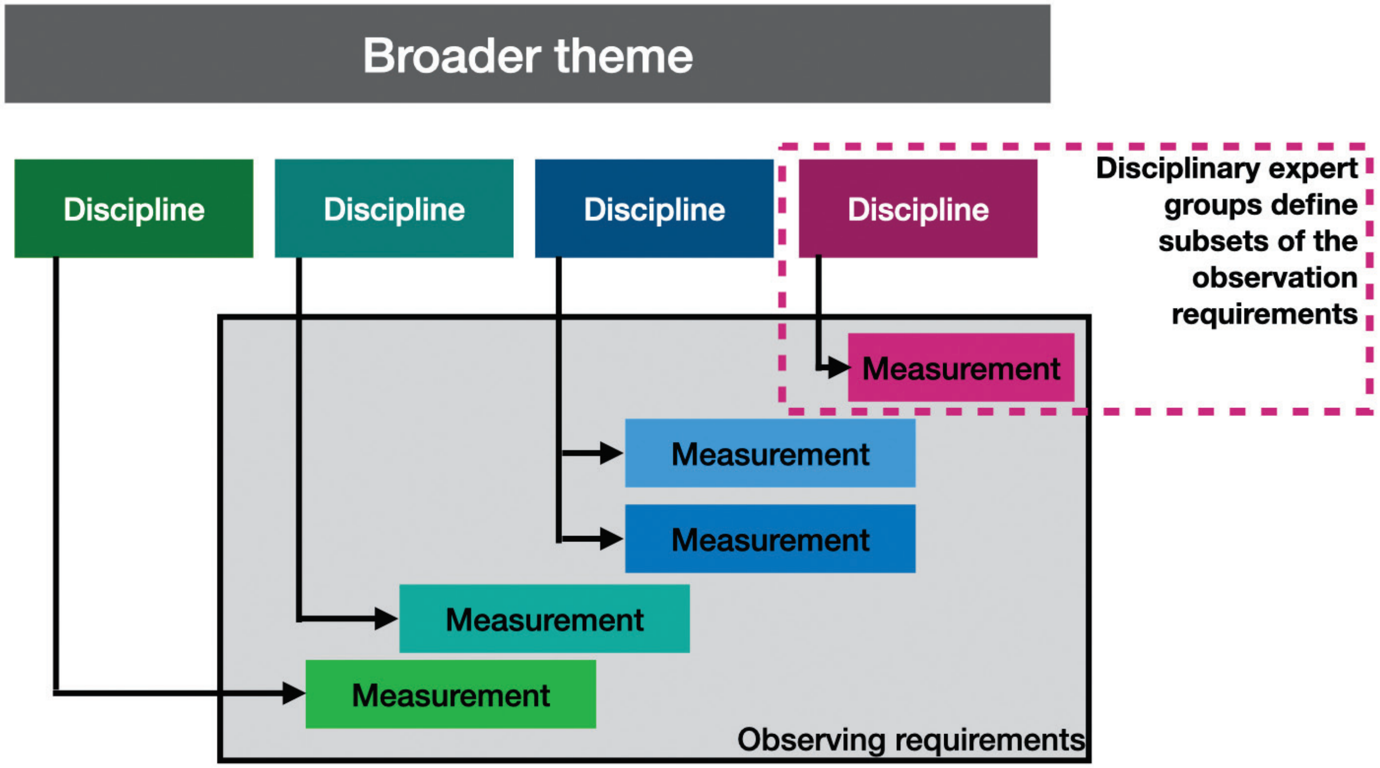

FIG. 2. Generic type of station model systems for coordinating observations. Requirements for an observing site are developed by aggregating observing element requirements from two or more disciplines.

observing stations according to those specifications. A primary goal of this approach is producing data that are directly comparable between locations, as they are generated by the same instruments with particular collection requirements. Stations have a reliable set of clustered measurements that provide the context required for both scientific process studies and broader interpretation. System specifications allow for adding new sites, though they can make it difficult to integrate existing facilities into the network. The downside of this approach is that there may be a very substantial investment required to establish a new station. Specific instrumentation, which often has high associated costs, can be fundamental to these directly comparable sites.

The GCW CryoNet observing system is a prime example of such a type of system. CryoNet has relatively limited requirements for station status, requiring measurement of at least one cryosphere component, a commitment to at least four years of observations, compliance with data and metadata standards, and competent staff.

Central Question Type: The third major approach is the central question framing. This is used by observing systems with operations-oriented goals, where actionable information is the core aim of the efforts. Instead of coordinating and disseminating observations, observing systems with central question framing gather observations through some sort of consensus-building process (e.g., GEOGLAM, Cripe and Jarvis, 2020; Jarvis, 2020) to develop resulting products. These observing systems rely on working groups (or staff at participating institutions) to process and synthesize those observations (Fig. 3). Development of new and improved analysis techniques is a critical part of this approach. Earth observations, being integral to addressing a particular organization's central questions, must meet the standard needed to provide the relevant information. Requirements for observing approaches are developed from the needs of the organizations' analysts rather than sourced from the larger community (e.g., Whitcraft et al., 2015).

Evaluating Observing System Models in the Context of Arctic Requirements

These three core types of observing system approaches each have strengths and weaknesses with regards to the requirements identified above for an AOF (Table 1).

Essential variables can, if developed with representatives from a number of user groups, meet the information needs of a range of sectors. The central question approach, where observation standards and requirements vary between groups responsible for analyses and reports, is particularly well-suited for incorporating observations from a number of sectors. Flexible technology requirements and the ability to leverage less mature observation approaches can be a feature of both the essential variable approach and the central question model. The station model approach has particular strength in coordinating observations between disciplines.

TOWARDS IMPLEMENTATION OF AN ARCTIC OBERVING SYSTEM: SHARED ARCTIC VARIABLES WITH CLUSTERED OBSERVATIONS INFORMED BY MULTIPLE STANDARDS

Here we describe an observing system type or model that builds on deliberations at the 2020 AOS and anticipates the ramping up of the SAON ROADS process. The approach draws on and refines the most relevant elements of the global and regional observing systems listed above. The initial conception of an essential Arctic variable framework for Arctic observations came from the SAON ROADS Task Force, having emerged from reviews of existing observing networks (Starkweather et al., 2021). This conception was presented at AOS 2020 as a launching point for discussion at the summit (Starkweather et al., 2019). The additional requirements described in the "Arctic Observing System Requirements" section of the present paper were largely a product of discussions at the AOS (Pope et al., 2020), which led to a need to more closely evaluate the essential variable type against a broader set of concerns.

The concept of SAV, while evolving out of the essential variables framework, also includes aspects of the station model approach by defining measurement standards as a combination of requirements and clusters of linked observables. The central question framework, while meeting many of the needs of the AOF, including building a community of practice, relies on a centralized or distributed body for analysis rather than making the underlying observations more widely available, which is a requirement of the AOF.

Shared Arctic Variables

The SAV framework builds on the concept of essential variables, as defined in a number of different observing contexts, but adapts it to Arctic settings in such a way as to meet the five overarching requirements for an observing system detailed under our "Requirements" heading. The essential variables concept was introduced in the context of observations supporting weather forecasting and extended to tracking and prediction of climate states. To qualify as essential climate variables (ECVs), observations thus have to meet three criteria: relevance in describing the state of the climate system at the global scale, technical and scientific feasibility, and cost-effectiveness (of measurements, mostly through coordinated observations using interoperable approaches) (Bojinski et al., 2014). The GOOS framework for essential ocean variables (EOVs; Lindstrom et al., 2012) adopts the ECV approach, with a focus on physical, chemical, and biological processes (including at the regional scale), and emphasis on societal needs as a key constraint (Miloslavich et al., 2018).

In what ways are SAVs distinct from these existing essential variable concepts, and why is there a need for explicitly distinguishing such shared variables? Participants of AOS 2020 recognized four aspects of Arctic observing that are unique and that led to refinement of essential variables into SAVs:

1) The role of Indigenous Peoples of the Arctic as knowledge and rights-holders who observe, derive benefits from, and are impacted by changes in Arctic social-environmental systems in ways that cut across multiple subsystems and sectors.

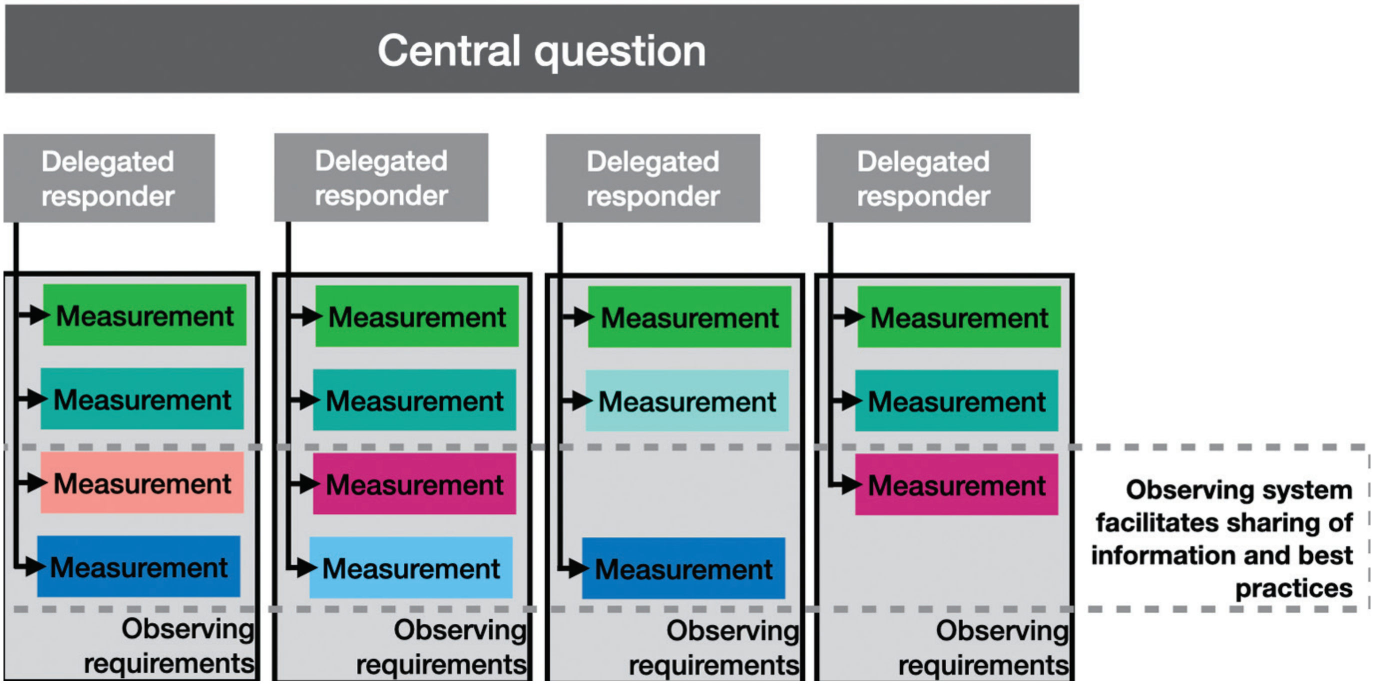

FIG. 3. Generic type of central question systems for coordinating observations. Core questions are identified as the motivation for the observing system, and answering these questions is delegated to expert or regional groups. Observations are accessed as required to address the questions.

2) The breadth of sectors, disciplines and Earth-system components that are tied to Arctic observing needs; these needs exceed the scope of other frameworks, which are limited by a given disciplinary or system-component focus (e.g., climate, oceans, biodiversity). Arctic observing, conversely, ties directly into multiple governance, planning, and decision-making contexts.
3) The lack of resources to address Arctic-specific challenges to observing system implementation, including harsh environmental conditions and presence of snow and ice.
4) Unique aspects of the natural environment, such as the key role of the cryosphere and the disproportionate importance of shelf processes and land-ocean interaction.

Consequently, SAVs need to comprise Indigenous-led benefit identification and regionally identified science and decision-making needs, and tie into essential variables of global networks (Starkweather et al., 2021). In other words, SAVs represent measurable phenomena or processes that are important enough to multiple communities/sectors to make it worth the work to coordinate their acquisition across the Arctic observing community. Replacing “essential” with “shared” recognizes that the strength of an AOF is in being able to coordinate between groups. What is essential to one community may not be to another.

In the SAV context, “shared” implies that more than one sector or organizational community is involved in the collection or use of the information. For example, interests by both Indigenous users and the fisheries industry would connect through an SAV by sharing observations, requirements, and information across sectoral boundaries. Variables are measurable phenomena or processes for which information gathered through observation is important. They should be specific enough that it is possible to define a measurement standard, but not so specific that the information loses potential value in a sharing context. “Sea ice thickness” would be a better candidate SAV than either “sea ice” or “mean undeformed sea ice thickness.” The specific threshold for “important” would be identified through collaborative or coproduction approaches, with the SAON ROADS process viewed as an overarching framework facilitating such work. Figure 4 presents two examples of potential SAVs: 4a shows sea ice thickness, and 4b shows coastal erosion rates. Each indicates potential observation sources on the right and information user groups on the left (though not an exhaustive list) and outlines observing requirements to meet the different user groups’ information needs.

SAV are distinct from, but not meant to supplant or compete with, globally defined essential variables. The introduction of an Arctic-specific observing framework is not meant to suggest in any way that the climate and ocean essential variables are not also essential in the Arctic, but rather that there are additional observational needs and requirements in the region that are not met by the larger systems. Essential variable requirements, as defined through GCOS, GOOS, or others, should be included in the observing standards defined for a particular SAV where appropriate, just as GCOS ECVs and GOOS EOVs exhibit some overlap.

It is important to emphasize that SAVs are not the only essential variables, the only variables/observables in the

Arctic with value, or even necessarily those with the most value to any particular group. Just because multiple sectors need access to some observations does not mean they are inherently more valuable than observations that are only needed by one group. Rather, the logistical and bureaucratic process of coordinating a particular type of observation across sectors is not needed (or worthwhile) when other sectors do not require access to the product. If scientific researchers require measurements of snow grain size that nobody else has a use for or means of collecting, snow grain size can be both important and a poor candidate for a SAV.

The GCOS process has identified the value of keeping the list of essential variables manageable (GCOS, 2010), and an AOF should strive to do the same. There are nearly limitless possible observable variables in the Arctic, and individual researchers and communities may be incentivized to get their particular interest listed as a SAV to increase its perceived value. It must be clear to funding agencies and to the research community that this SAV process is meant to facilitate sharing of resources, not definitively declare that certain variables are more important than others.

Multiple Observing Standards with Clustered Observation Recommendations

Standards are both critically important to the success of an AOF based on shared data and an impediment to implementation. To define a standard, the Arctic observing community (split across many sectors and backgrounds) must agree on how something should be measured. Ultimately, a single standard for any particular variable will not be possible under most circumstances: residents of an Arctic Indigenous community will observe and measure sea ice thickness differently than a satellite-based altimeter. Figure 4a shows two complementary observing standards for a single SAV, "Sea ice thickness."

By defining a set of potential standards per variable, agreed-on approaches to observation can create opportunities for the broadest possible contributions while maintaining some of the benefits of a standard, such as known (or at least describable) data quality, potential for comparison between observations, and instructions for new observers. The observing requirements of climate modelers and subsistence hunters will never exactly converge. Instead, the SAV definition process is meant to identify the opportunities for shared benefit. In the interest of inclusivity and leveraging the greatest number of potential observers, instructional documents and videos should be produced so that non-experts can be quickly trained in the relevant protocols.

The standards for a SAV should include more than the direct measurements of the variable itself. Instead, a standard should include a set of recommended additional observations generated by the communities and sectors that are interested in the observations of the SAV. AOS 2020, and specifically the contributions of Indigenous Peoples, who emphasized the benefits of drawing on a food security lens, highlighted the importance of clustered observations centered around different societal benefits and applications (Fig. 4). Scientific observations are of little value without additional context. Clustered observations are a means to include that context in the observing standard and best practices for any SAV. Furthermore, defining controlled vocabularies for use in SAVs can be beneficial for future data interoperability and shared understanding of terminology. Such work can leverage the efforts of existing working groups, such as the SAON Semantics and Vocabularies Working Group.

This approach for defining observing requirements is illustrated in Figure 4a, where two separate observing requirement clusters are defined for a proposed sea ice thickness SAV. Cluster A is designed to meet the needs of subsistence hunters and other users of the coastal ice in the region who need detailed information about the ice conditions near shore. Cluster B aims to meet the needs of the climate modeling and ice forecasting community and the shipping industry, providing regular pan-Arctic maps of ice thickness. Cluster B meets (or exceeds) the requirements for the thickness part of the GCOS Sea Ice Essential Climate Variable, showing how the SAV framework can work in coordination with global observing frameworks.

The vision here is to build a library of observing standards (drawing on best practices approaches articulated by Pearlman et al., 2019, for the ocean observing community), with multiple standards available per SAV. A sea ice motion variable may come with standards developed for shore-based observations, for autonomous buoy observations, and for remote sensing platforms. Each of these would include both what is recorded (e.g., drift speed and direction) for that particular variable, and a set of co-observables that provide the relevant context (e.g., wind speed and direction, near-surface currents) that would depend on the type of observation and the setting in which it is measured. The requisite instrumentation, time, and effort for additional measurements in a cluster should be commensurate with that of the main variable: if a supplemental measurement requires an expensive instrument for what is otherwise a relatively low-cost observation, it is unlikely to be made. These clusters would be determined by the expert group that defines the standards, with input from the observing and user communities.

Review and Amendment Process

Like in the GOOS and GCOS models, an initial set of SAVs would be generated by expert panels. In developing a SAV, an expert panel representing relevant sectors and interest groups would convene to draft an initial definition for the variable. This would consist of representatives from local communities, relevant scientific disciplines, operational agencies, and private industry. Funding may be necessary to ensure participation by Indigenous community representatives and the private sector. Much of this process

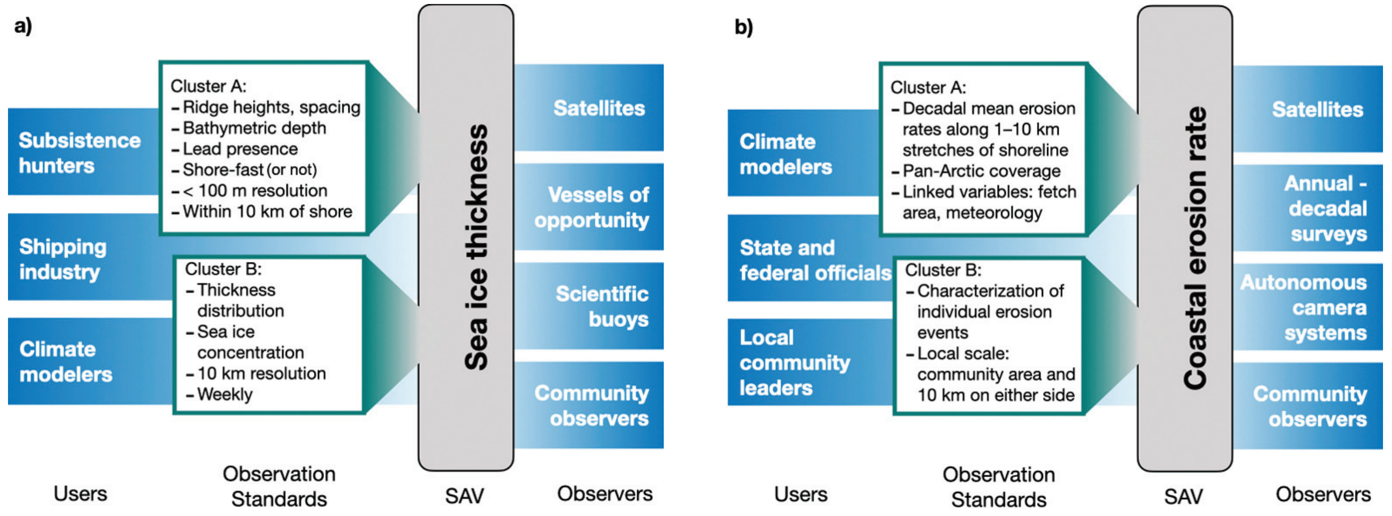

FIG. 4. Conceptual model for a shared Arctic variable (sea ice thickness), with a set of observers contributing to two measurement standards/clusters, which are then available for relevant user groups. The two observing standard clusters are designed to meet the information needs of groups of users; Cluster B also meets the requirements for the GCOS sea ice essential climate variable.

has been laid out by SAON ROADS (Starkweather et al., 2021). This section is meant to add detail necessary to meeting the requirements identified through AOS 2020 discussions.

It is not practical to generate an all-encompassing set of SAVs all at once. Rather, SAON ROADS, through the expert panel process, is in a position to develop a starting set of SAVs that is reflective of urgent needs and common priorities of Arctic rights-holders and stakeholders. Even such focused activities come with challenges. However, societal benefit assessments, such as the International Arctic Observing Assessment Framework (STPI-IDA and SAON, 2017) and socio-economic assessment frameworks (Dobricic et al., 2018; Strahlendorff et al., 2019), provide some initial guidance on a starting set of SAVs by identifying where observations can have direct impact on areas of societal need.

In parallel with this initial set, SAON should develop a process through which new SAVs can be proposed. If the onus for proposing a new SAV is on the communities and user groups who are interested in using those observations, the process of developing the proposal should cover much of the work that goes into defining a SAV. To be put forward, proposals would require support from two or more groups (e.g., fisheries industry representatives and research biologists). That process would identify experts in the collection and use of the observable, who could then contribute to defining the observing standards. Public feedback on SAV proposals would solicit additional interest in the potential SAV and would further refine observing standards or add to paired measurement clusters or both.

CONCLUSION

Drawing on deliberations at the 2020 AOS, we have briefly reviewed three different categories of observing systems, specifically the essential variable, station model, and central question types. Currently, all three are reflected by observing system efforts underway in the Arctic. The need for improved coordination of observations and enhancement of societal benefits derived from these programs has been emphasized in a variety of contexts, leading to the call for a roadmap to be generated by SAON's ROADS process. A successful AOF emerging from the ROADS process will have to integrate aspects of essential variable and station model framework types and draw lessons from the central question approach. The essential variable model has emerged as the core approach to channel limited observing resources into activities that address the most pressing needs through efficient collaborative approaches. In the Arctic, this goal can best be met through establishment of a shared Arctic variable concept. SAVs combine the strengths of existing global and regional observing frameworks to foster systems that leverage the limited observing resources in the Arctic to better meet the information needs of different groups with rights and interests in the region, in particular, Arctic Indigenous Peoples.

Station model–type observations are highly relevant in the Arctic because of logistics and operational challenges. As SAON ROADS gets underway, a combination of the SAV and station model approach may help in advancing the broader concept and implementation of coordinated observations. Choosing sites of significance to Indigenous Peoples of the Arctic in a planning and decision-making context may help avoid problems stemming from limited observing sites and biased placement (Metcalfe et al., 2018). At the same time, focusing initial efforts on a small set of well-selected sites will aid codesign and comanagement of observing systems.

In the context of AOS 2020, a number of regions were identified as suitable for pilot programs, including the Bering Strait and Barents Sea regions, where international and cross-sectoral engagement within the framework can be facilitated. Indigenous communities are intimately familiar with the environmental systems of these areas, and efforts such as the Indigenous Sentinels Network of The Aleut Community of St. Paul, in Alaska, have built capacity and expertise in the development of Indigenous, community-driven observing activities. The regions also have a longer history of scientific research programs and are relevant for a number of industries, including fisheries, all of whom have an interest in, and can potentially contribute to observing programs.

As the SAON ROADS process gets underway, it should facilitate identification of an initial set of SAVs that represents key information needs across Arctic rights-holders, stakeholders, and the observational community, while being sensitive to historical and ongoing power and resource imbalances. Indigenous communities must be included in the process, with the funding necessary to fully engage alongside scientific, operational, and industry communities. Once an initial set of SAVs has been defined along with observing requirements and associated information, the process can be expanded to add SAVs as needed. The approach for creating a new SAV must be inclusive in order to develop observing cluster requirements that account for the information needs of a broad swath of users.

Since the 2020 AOS, SAON has established a ROADS Advisory Panel with significant Indigenous community involvement. At the 2022 AOS, Working Group 4: System Implementation took up discussions on SAVs and proposed a process for establishing expert panels to define SAVs. Two pilot projects, Research Networking Activities for Sustained Coordinated Observations of Arctic Change (RNA CoObs) and Pan-Arctic Observing System of Systems Implementing Observations for Societal Needs (Arctic PASSION), are developing proposals for themes around which to start the expert panel process.

Arctic observing resources are limited. The observing community will benefit from making better, more coordinated use of these resources. A framework that facilitates the inclusion of all potential observers, with integrated information-sharing mechanisms and training resources, can make this possible. Ultimately, this calls for the emergence of communities of practice around particular sectors or clusters of observations. Such a community is best served by the collaborative development of engagement protocols and best practices, the latter along the lines of efforts emerging out of the OceanObs'19 community (Pearlman et al., 2019). If implemented in a deliberative and inclusive process, the SAV approach could provide a platform for fostering such communities of practice in the Arctic, a common language, and a common framework through which to build collaborative relationships, while helping grow connections between observers and information users.

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