Shared Arctic Variable framework to link global and Arctic regional and local observing system priorities and requirements

Authors:
Alice Bradley, Hajo Eicken, Olivia Lee, Anna Gebruk, Roberta Pirazzini

Addresses:
Alice Bradley
https://orcid.org/0000-0002-6953-5260
Williams College
18 Hoxsey St. Williamstown, MA 01267
alice.c.bradley@williams.edu
Hajo Eicken,
https://orcid.org/0000-0002-9718-9406
International Arctic Research Center, University of Alaska Fairbanks
2160 Koyukuk Dr., Fairbanks, AK 99775-7340, USA
heicken@alaska.edu
Olivia Lee,
https://orcid.org/0000-0003-2841-7812
International Arctic Research Center, University of Alaska Fairbanks
2160 Koyukuk Dr., Fairbanks, AK 99775-7340, USA
oalee@alaska.edu
Anna Gebruk,
https://orcid.org/0000-0002-2516-8286
Changing Oceans research group, the University of Edinburgh / Lomonosov Moscow State University Marine Research Center
Grant Institute. The University of Edinburgh, King's Buildings, James Hutton Road, Edinburgh, EH9 3JW
Anna.Gebruk@ed.ac.uk
Roberta Pirazzini
https://orcid.org/0000-0003-3215-4592
Finnish Meteorological Institute
Erik Palmenin aukio 1, 00560 Helsinki, Finland
roberta.pirazzini@fmi.fi

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Abstract

The geographic setting and interests by 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-sector prioritization and refinement from the local to the pan-Arctic scale, leveraging limited resources in challenging environmental settings. We evaluate several different types of observing systems relative to the needs of the Arctic observing community and information users to identify the frameworks' respective strengths and weaknesses. A typology of three approaches emerges from this assessment: Essential Variable, Site Model, or Central Question Types. The concept of Shared Arctic Variables (SAV), emerging from the Arctic Observing Summit 2020 and prior work by the Sustaining Arctic Observing Networks Road Mapping Task Force, is defined and assessed against the requirements. SAVs align with essential variables as defined, e.g., by global observing frameworks, in that they guide coordinated observations across processes of interest to multiple sectors. SAVs are responsive to the information needs of Arctic Indigenous Peoples and draw on their capacity to co-design and co-manage observing efforts. They are tailored to accommodate the logistic 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

1. Introduction and Background

A truly coordinated Arctic Observing System would make for better observations, more efficient use of resources, increased coverage, and expanded cooperation between information users from different sectors and the observing community. 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. These efforts often have conflicting requirements, all the while largely excluding Indigenous communities that could benefit from the research investment in the region.

The Arctic Observing Summit (AOS, arcticobservingsummit.org), the biennial meeting that serves as an opportunity for the Arctic observing community to come together, exchange ideas and coordinate joint action, has synthesized discussions and made recommendations over several years of meetings between 2013 and 2020 towards a coordinated Arctic Observing System or System of Systems (Lee et al., 2015; Murray et al., 2018; AOS, 2020). This system would need to meet a variety of stakeholder needs, 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 local to global observing needs.

This contribution builds on deliberations at the 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 most recent AOS, we explore essential aspects of the implementation of a coordinated observing systems framework. Specifically, we define the concept of Shared Arctic Variables (SAV) drawing on AOS 2020 and the relevant strengths of extant observing systems and discuss implications for the establishment of coordinated Arctic observing systems.

1.1 Global Observing Systems

Global observing systems provide international structures for prioritizing, coordinating and implementing observations around areas of common interest. A well-developed observing framework facilitates national, local community and/or private sector observing efforts to address societal needs, while reducing replication of efforts because data is 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, with the observing community tasked with accomplishing measurements of these variables according to some pre-defined standards that are then archived in a coordinated and accessible manner. Who carries out these measurements and with what level of commitment varies between systems. For the larger observing systems, the contributions are typically managed in a system-of-systems approach, with national and even international observing networks addressing parts of the observing goals. The primary contributors to the Global Climate Observing System (GCOS) are major agency programs like Copernicus (the European Union's Earth Observation Program; 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.

1.2. The Arctic Setting

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 under-sampled with in situ measurements (e.g., Riser et al, 2016; Wohner et al., 2021), leaving sparse data in 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 pushing a trend towards increasingly seasonal ice cover (Perovich, 2011) and higher drift speeds (Spreen, Kwok and Menemenlis, 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 under-sampled Arctic Ocean (e.g., Lee et al., 2019; Argo, 2000).

Weather stations and balloon soundings are similarly sparse in the Arctic (Durre, Vose and Wuertz, 2006), again largely due to the 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., MOSAiC, mosaic-expedition.org).

Darkness and frequent cloud cover likewise limit remote sensing observations, where visible imagery (a staple of many remote sensing efforts at lower latitudes) is severely limited throughout the year. At the same time, the geometry of polar orbits mean 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.

Terrestrial 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 that Arctic field studies and sustained observations are biased towards the immediate vicinity of Toolik Lake in Alaska and Abisko in northern Sweden (Metcalfe et al., 2018). In contrast, in the Arctic community-based or bottom-up observing or monitoring efforts (such as the Yukon River Intertribal Watershed Council water quality monitoring program) are disproportionately more common relative to top-down, large-scale observing efforts (such as the United Nations Global Environment Monitoring System for freshwater) as compared to 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).

Indigenous communities thrive in the region. Inuit, Aleut, Athabaskan, 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).

1.3. The State of Arctic Observing Systems

There is a clear need for sustained, coordinated Arctic observations that track sub-seasonal 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; Tjernström et al., 2019; Zacharova et al., 2019; Lee et al., 2019). The Sustaining Arctic Observing Networks

(SAON) initiative, the AOS's (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.

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 timescales, 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; discussed in more depth below) 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 evolving as a program with much sparser observations that are still being refined in terms of core variables and requirements (Key et al., 2015). While somewhat broader in terms of processes and variables covered, the Circumpolar Biodiversity Monitoring Programme (CBMP; 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 scale 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, e.g., 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 associated with field stations or laboratories, e.g., the Svalbard Integrated Arctic Earth Observing System (SIOS, 2020), typically encompass a broad range of observations within a specific geographic locale. SIOS 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 a Data Management System Working group that promotes open access to data, facilitates adoption and implementation of data standards, and engages with partners across disciplines and geographic scales to facilitate data management practices that are cost-effective and sustainable (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; Straneo et al., 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. In contrast, a regional observing system established using the Shared Arctic Variable approach, described in detail below, would include a more equitable process to engage a broader sector of society – notably Arctic Indigenous People and communities – in defining observing priorities and leveraging existing observing efforts. It would also need to be inclusive of a greater wealth of ecological and socio-economic observations.

These different types of sustained observations mostly evolve 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 U.S. Arctic Observing Viewer team (arcticobservingviewer.org). 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 (ROADS) 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., submitted). This contribution addresses a core problem central to the ROADS process, i.e., the development of a framework of core variables ("essential variables") which address societal benefit areas and information needs and which are specific enough to guide observing system requirements and engineering design. Specifically, 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.

2. Arctic Observing System Requirements

For an organized, cross-sector, 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. For the purposes of this discussion, the proposed system is referred to as the Arctic Observing Framework (AOF), to differentiate it (at least by acronym) from the Arctic Observing Summit (AOS). Many of these requirements have been identified in the ROADS process (Starkweather et al., submitted). Complementing the in-depth discussion by Starkweather et al. (submitted) and the SAON Roadmapping Task Force, we provide a brief perspective based on discussions at the 2020 Arctic Observing Summit which highlighted five interrelated requirements for the system, specifically that it:

(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, submitted) 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 such as limited internet access and other communication hurdles.

(4) Leverages limited resources: In order to leverage limited observing resources in the face of 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. 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.

3. Perspectives on Selected Observing System Approaches

Having briefly reviewed background and attributes of Arctic observing system implementation, we now examine key aspects of established observing networks as relevant to the Arctic, in particular as applicable to the SAON ROADS process. For the purposes of this analysis, we consider five global and two regional observing systems. Collectively, these systems use different approaches for organizing and coordinating observations, including organizing around Essential Variables, Site Models, 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 (Table 1).

3.1 Survey of Selected Arctic-relevant Observing Systems

Global systems here include the Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS), the Global Cryosphere Watch (GCW), Group on Earth Observations Biodiversity Observation Network (GEOBON), and Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM). Regional systems include the Svalbard

Integrated Earth Observing System (SIOS) and the proposed Greenland Ice Sheet Ocean Observing System (GRIOOS).

3.1.1. GCOS: Global Climate Observing System

Established in 1992 by the WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, UNEP, and the International Council for Science (ICSU) 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, 2020). Contributed observations are gathered through major institutions, agencies, and national programs, with cooperation mechanisms supporting efforts in under-resourced regions (Plummer, Lecomte and Doherty., 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.

3.1.2 GOOS: Global Ocean Observing System

The Global Ocean Observing System (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 feeds into the Global Earth Observation System of Systems (GEOSS) together with the GCOS and others. GOOS utilizes the Framework for Ocean Observing based on the 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. Some variable standards rely on instrumentation with limited variability (e.g., ARGO floats, Lindstrom et al., 2012), but the framework includes a pilot project process for integrating new technologies (Moltmann et al., 2019). Regional Alliances offer an entry point into the GOOS network for less mature observing programs (Moltmann et al., 2019).

3.1.3 GCW: Global Cryosphere Watch (CryoNet)

The Global Cryosphere Watch (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 (WIGOS). 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 measurements for investigation of the coupled systems (GCW, 2018).

3.1.4 GEOGLAM: Group on Earth Observations Global Agricultural Monitoring Initiative

The Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM) is aimed at increasing market transparency and improving 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 is 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 Observing (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 R&D 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.

3.1.5 GEOBON: Group on Earth Observations Biodiversity Observation Network

Group on Earth Observations Biodiversity Observation Network (GEOBON) is a global biodiversity observation network that contributes to effective management policies for the world's biodiversity and ecosystem services. GEOBON facilitates national biodiversity observing networks (BONS) through use of Essential Biodiversity Variables (EBVs) and produces higher-level synthesis products (Pereira et al, 2013). GEOBON is a part of the 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 and Marques et al, 2014). Data contributions to GEOBON come through regional/national BONs (SCBD, 2010), of which there are currently at least 25 established ones 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 (GEOBON, 2008): many core measurements are low-tech (e.g., species counts) (Pereira et al, 2013) which makes it relatively low-cost to set up.

3.1.6 SIOS: Svalbard Integrated Earth Observing System

Svalbard Integrated Earth Observing System (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 Optimisation Advisory Group comprises a range of national and international academic and research institutions and agencies and 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 system effort to coordinate between variables. Generally, the observations address the needs of the scientific community; with most ultimately motivated by understanding climate (van den Heuvel et al, 2019). Sharing of data and observing standards reduces duplication of effort in the high-cost region (SIOS, 2016).

3.1.7 GRIOOS: Greenland Ice Sheet Ocean Observing System

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

3.2 Observing system typologies

Among the global and regional observing systems considered here, three types of approaches have emerged and are discussed in more detail below: essential variables, site models, and central questions.

3.2.1 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 EV approach has been used successfully by GCOS and GOOS.

The EV model provides a flexible, clear mechanism for additional contributions. Potential new observers can look up the measurement standards for a particular variable, and if they can meet those standards with a validated measurement protocol, they can contribute observations. This approach is straightforward 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.

3.2.2 Site Model Type

The second major type of observing system is organized around Site Models, as seen with GCW and the proposed GRIOOS. Figure 2 illustrates this process: Some set of measurements is established by an interdisciplinary expert committee as a generic site, and participating nations/institutions/research facilities are tasked with building observing sites according to those specifications. This model has the advantage of producing data that are directly comparable between sites, as it is generated by the same instruments in the same manner. Sites have a reliable set of clustered measurements, that provide the context required for both scientific process studies and broader interpretation. It is straightforward to open an additional site, as the specifications have been pre-determined. The down-side of this approach is that there may be a very substantial investment required to open a site. 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.

3.2.3 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, Jarvis, 2020; Cripe and Jarvis, 2020) to develop resulting products. They rely on working groups (and/or staff at participating institutions) to process and synthesize those observations. Development of new and improved analysis techniques is a critical part of this approach. Earth observations, being integral to addressing the 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, Becker-Reshef and Justice, 2015).

3.3 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 Arctic Observing Framework, summarized in 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 site model approach has particular strength in coordinating observations between disciplines.

4. Towards Implementation of an Arctic Observing 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 Road Mapping Task Force, having emerged from reviews of existing observing networks (Starkweather et al., submitted). It was presented to the AOS 2020 as a launching point for discussion at the summit (Starkweather et al., 2019). The additional requirements described in Section 2 were largely a product of discussions at 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 Shared Arctic Variables (SAV) concept evolved from the Essential Variable type, e.g., as adopted by GCOS or GOOS, as an outcome of deliberations by the SAON Road Mapping Task Force at the summit to address such concerns and the requirements identified in Section 2. The SAV approach includes aspects of the Site Model approach by defining measurement standards as a combination of requirements and clusters of linked observables. The Central Question framework, meeting many of the needs of the Arctic observing framework including building a community of practice, relies on a centralized or distributed body for analysis rather than making the underlying observations more widely available.

4.1. Shared Arctic Variables

The SAV framework builds on the concept of Essential Variables (EV) as defined in a number of different observing contexts, but adapted to Arctic settings in such a way as to meet the five overarching requirements for an observing system detailed in Section 2. The EV 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 Variable (ECV) 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 measurements need to be cost effective mostly through coordinated observations using interoperable approaches (Bojinski et al., 2014). GOOS' framework for Essential Ocean Variables (EOV; Lindstrom et al., 2012) adopts the ECV approach, with a focus on physical, chemical, and biological processes (including at the regional scale) and emphasis of societal needs as a key constraint (Miloslavich et al., 2018).

In what ways are SAVs distinct from these existing EV concepts, and why is there a need for explicitly calling out such shared variables? Participants of the AOS 2020 recognized four aspects of Arctic observing that are unique and led to refinement of EVs into SAVs:
(i) 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 sub-systems and sectors;

(ii) the breadth of sectors, disciplines and earth system components tied to observing needs that exceed the scope of other frameworks with disciplinary or system component focus (e.g., climate, oceans, biodiversity) and that tie directly into multiple governance, planning, and decision-making contexts;

(iii) the lack of resources to address Arctic-specifically challenges to observing system implementation, including harsh environmental conditions and presence of snow and ice;

(iv) unique aspects of the natural environment such as the key role of the cryosphere or disproportionate importance of shelf processes and land-ocean interaction.

Consequently, SAVs need to comprise Indigenous-led benefit identification, regionally identified science and decision-making needs, and tie into essential variables of global networks (Starkweather et al., submitted). 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 Arctic observing framework 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 and/or use of the information. For example, interests by both Indigenous users and the fisheries industry would connect through an SAV with sharing of observations, requirements, and information across sector 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 co-production approaches, with the SAON ROADS process viewed as an overarching framework facilitating such work. Figure 4 shows an example of sea ice thickness as a SAV, with potential observing and information user groups identified (though not an exhaustive list) and observing requirements outlined.

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 EVs 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.

It is important to emphasize that SAVs are not the only essential variables. Shared Arctic Variables are not 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 make them inherently more valuable than observations that are only needed by one group. Rather, the logistical and bureaucratic process of coordinating an 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 not a good candidate for a SAV.

The GCOS process has identified the value in keeping the list of essential variables manageable (GCOS, 2010), and an Arctic observing framework 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 to definitively declare that certain variables are more important than others.

4.2. Multiple observing standards with clustered observation recommendations

Standards are both critically important to the success of an Arctic observing framework 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 from a satellite-based altimeter. Figure 4 shows two complimentary observing standards for a single SAV, “Sea ice thickness.”

By instead defining a set of potential standards per variable, there can be agreed-on approaches to observation that create opportunity for the broadest possible contributions while maintaining some of the benefits of a standard: known (or at least describable) data quality, potential for comparison between observations, and instructions for new observers. In 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 an 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. The 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 (see also Figure 5). 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.

This approach for defining observing requirements is illustrated in Figure 5: 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 be built 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 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, etc.) 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 on what is otherwise a relatively low-cost observation, it is unlikely to be made. These clusters would be determined by the expert group who defines the standards, with input from the observing and user communities.

4.3. Review and amendment process

Like 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 convenes 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 has been laid out by SAON ROADS (Starkweather, in press): this section is meant to add detail necessary to meet 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 Arctic rightsholders and stakeholders. Even such focused activities come with challenges. However, societal benefit assessments, such as the International Arctic Observing Assessment Framework (IDA, 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. Proposals would require two or more groups (e.g., fisheries industry representatives and research biologists) to put forward. 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 and/or add to paired measurement clusters.

5. Conclusions

Drawing on deliberations at the AOS 2020, we have briefly reviewed three different categories of observing systems, specifically the Essential Variable, Site Model, and Central Question

Type. Currently, all three of these 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 ROADS process will have to consider aspects of the first two observing system types. 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 that combines 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 the different groups, including in particular Arctic Indigenous Peoples, with rights and interests in the region.

Site 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 Site Model approach may help in advancing the broader concept and implementation of coordinated observations. In particular in choosing sites of significance to Indigenous Peoples of the Arctic in a planning and decision-making context may help avoid problems stemming from overrepresentation of a few limited sites (see Metcalfe et al., 2018, for some of the consequences). At the same time, focusing initial efforts into a small set of well-selected sites will aid co-design and co-management of observing systems.

In the context of AOS 2020, a number of regions were identified as suitable for pilot programs, including the Bering Straits and Barents Sea regions, where international and cross-sector 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 rightsholders and 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.

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. It would provide 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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Tables:

Table 1: Evaluation of the three types of observing frameworks with regards to the five identified Arctic system requirements.

	Essential Variable	Site Model	Central Question
Example systems	GCOS, GOOS, GEOBON, SIOS	GCW-CryoNet, GRIOOS	GEOGLAM, GCW
Addresses needs of many sectors?	Essential Variables are selected by expert groups: with the right composition, these expert groups could represent the needs of many sectors. The challenge would be in defining observing requirements that satisfy all relevant stakeholders.	Sites are typically designed for maximizing research utility, rather than for cross-sector needs.	Central question framings are typically focused on a particular area of concern or sector (e.g., agriculture).
Contributions from many sectors?	While in practice most contributed observations come from major observing institutions/ agencies, the model is open to observations from any source.	Sites are generally built/maintained by research institutions or national observing programs, but could be contributed by anyone given the resources.	Delegates/working groups draw from many sources, including across sector boundaries, to compile analyses and reports.
Technology flexible?	Technological requirements depend on how the observing requirements are set.	Site models are the most likely to have specific technology requirements.	Flexible observation requirements allow for easy adoption of new/different approaches.
Leverages limited resources?	Any observers that can meet the defined observation requirements can contribute, so it depends on the specific requirements.	Site models may lack flexibility in incorporating potential observations if the site requirements are too stringent.	Delegated working groups can focus on whatever observing resources are most relevant in their area.
Interconnected variables?	Essential variables are normally defined individually, though with effort requirements can be coordinated.	Site models are designed to coordinate measurement of interconnected variables.	Centrals typically focus on complex systems, where consideration of interconnected processes is critical for understanding.

Figure captions:

Figure 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.

Figure 2: Generic type of Site Model systems for coordinating observations. Requirements for an observing site are developed by aggregating observing element requirements from two or more disciplines.

Figure 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.

Figure 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 .

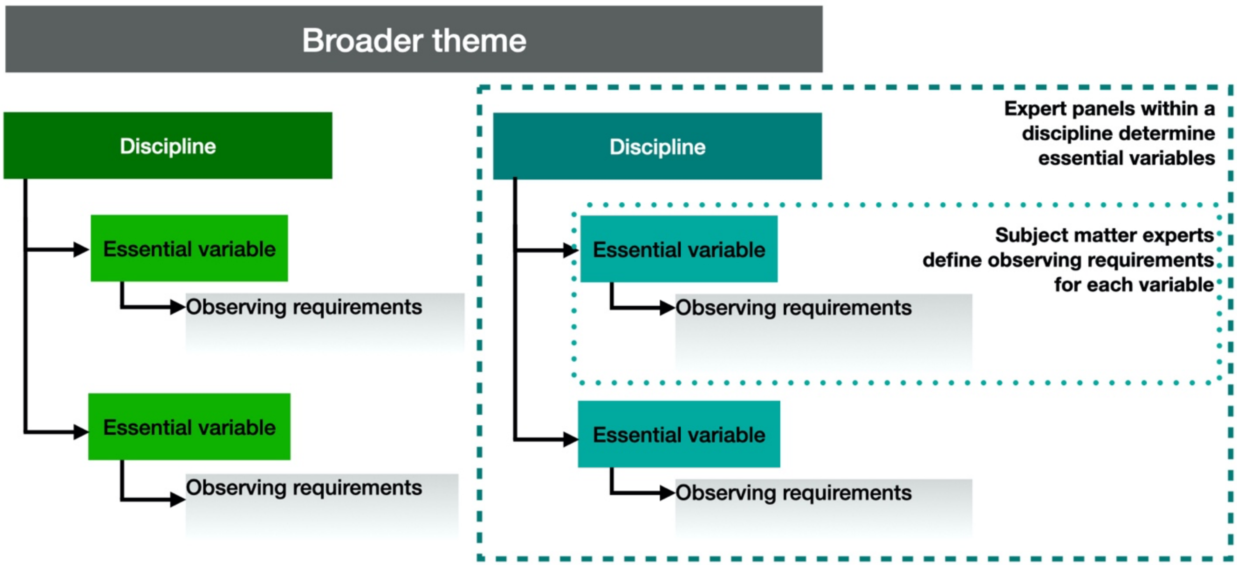

Figure 1 Generic type of Essential Variable systems for coordinating observations. Within each broader discipline, essential variables are selected by expert panels, then observing requirements for those essential variables are developed by subject matter experts.

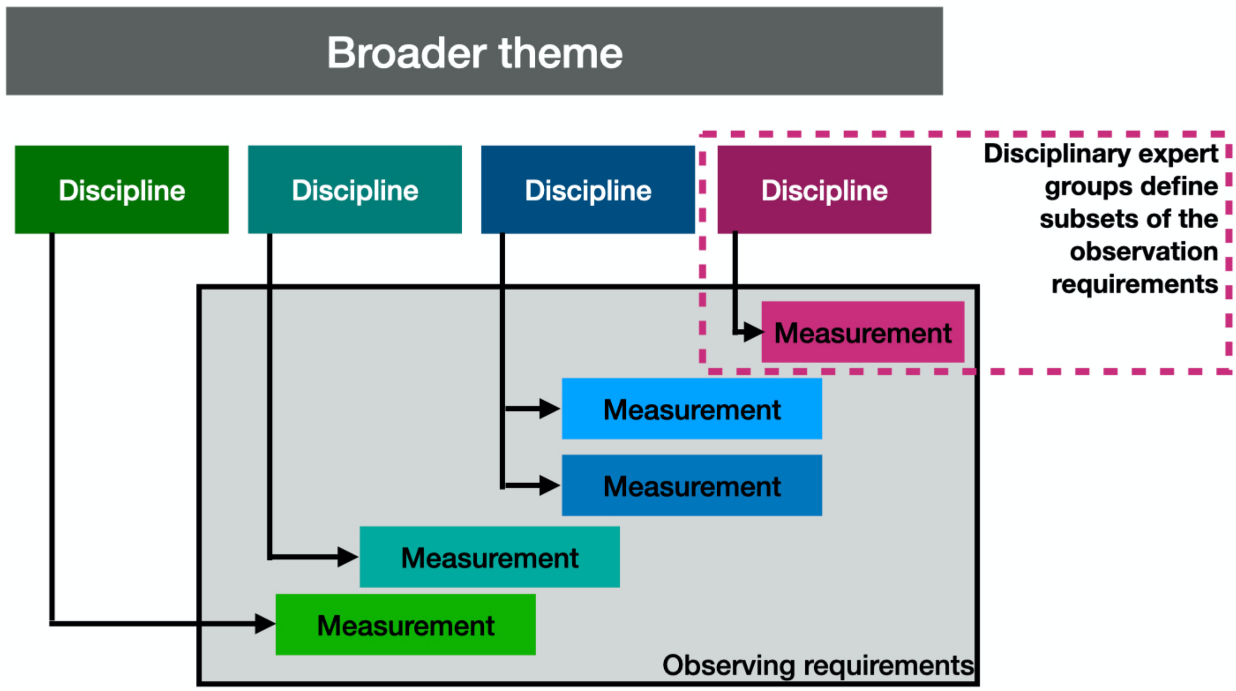

Figure 2 Generic type of Site Model systems for coordinating observations. Requirements for an observing site are developed by aggregating observing element requirements from two or more disciplines.

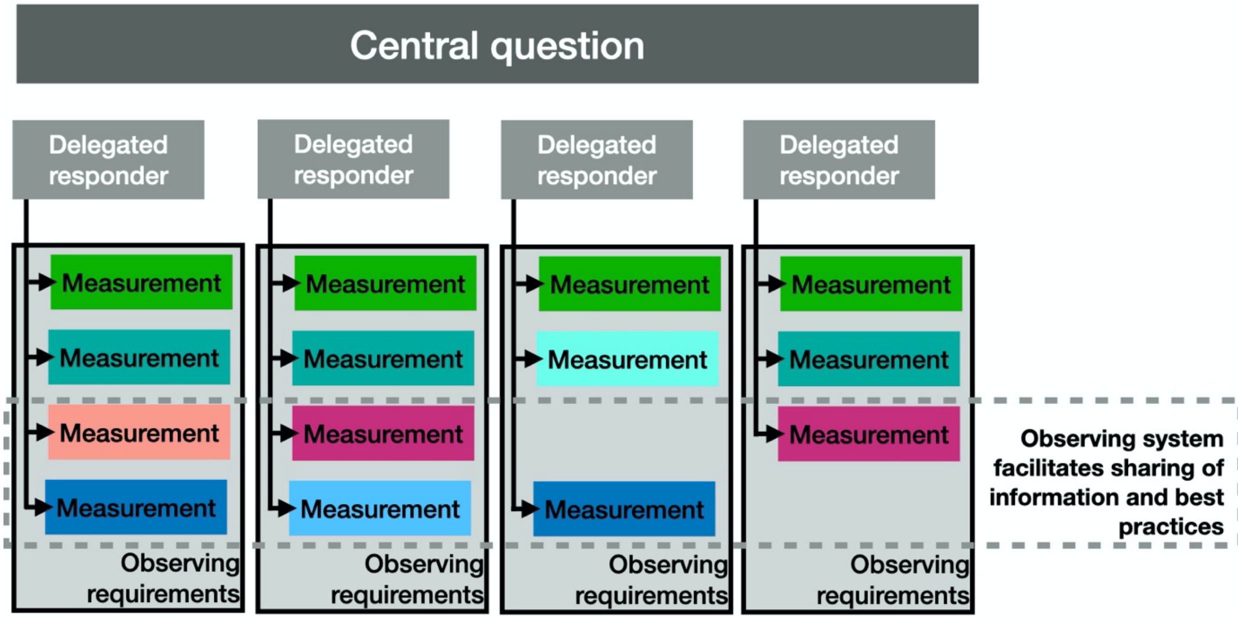

Figure 3 Generic type of Central Question systems for coordinating observations. Core questions are identified as the motivation for the observing system, and answering these questions is delegated to expert or regional groups. Observations are accessed as required to address the questions.

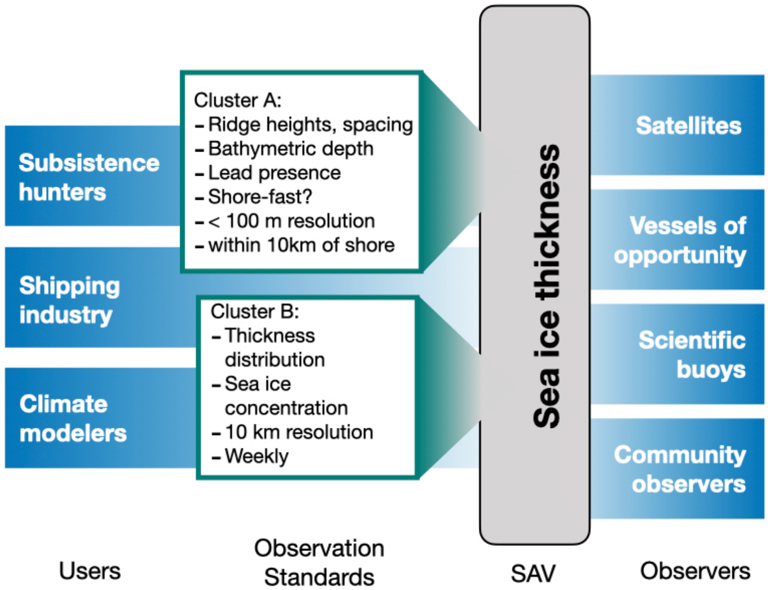

Figure 4 Conceptual model for a Shared Arctic Variable (Sea Ice Thickness) with a set of observers contributing to two measurement standards/clusters, which are then available for relevant user groups. The two observing standard clusters are designed to meet the information needs of groups of users; Cluster B also meets the requirements for the GCOS Sea Ice Essential Climate Variable.