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A New Structure for the Sea Ice Essential Climate Variables of the Global Climate Observing System

Thomas Lavergne, Stefan Kern, Signe Aaboe, Lauren Derby, Gorm Dybkjaer, Gilles Garric, Petra Heil, Stefan Hendricks, Jürgen Holfort, Stephen Howell, Jeffrey Key, Jan L Lieser, Ted Maksym, Wieslaw Maslowski, Walt Meier, Joaquín Muñoz-Sabater, Julien Nicolas, Burcu Özsoy, Benjamin Rabe, Wolfgang Rack, Marilyn Raphael, Patricia de Rosnay, Vasily Smolyanitsky, Steffen Tietsche, Jinro Ukita, Marcello Vichi, Penelope Wagner, Sascha Willmes, and Xi Zhao

ABSTRACT: Climate observations inform about the past and present state of the climate system. They underpin climate science, feed into policies for adaptation and mitigation, and increase awareness of the impacts of climate change. The Global Climate Observing System (GCOS), a body of the World Meteorological Organization (WMO), assesses the maturity of the required observing system and gives guidance for its development. The Essential Climate Variables (ECVs) are central to GCOS, and the global community must monitor them with the highest standards in the form of Climate Data Records (CDR). Today, a single ECV—the sea ice ECV—encapsulates all aspects of the sea ice environment. In the early 1990s it was a single variable (sea ice concentration) but is today an umbrella for four variables (adding thickness, edge/extent, and drift). In this contribution, we argue that GCOS should from now on consider a set of seven ECVs (sea ice concentration, thickness, snow depth, surface temperature, surface albedo, age, and drift). These seven ECVs are critical and cost effective to monitor with existing satellite Earth observation capability. We advise against placing these new variables under the umbrella of the single sea ice ECV. To start a set of distinct ECVs is indeed critical to avoid adding to the suboptimal situation we experience today and to reconcile the sea ice variables with the practice in other ECV domains.

KEYWORDS: Sea ice; Climate change; Climatology; Climate records

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Corresponding author: Thomas Lavergne, thomas.lavergne@met.no
Thomas Lavergne and Stefan Kern are co-first authors and contributed equally to this work.

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AFFILIATIONS: Lavergne*,[+]—Research and Development Department, Norwegian Meteorological Institute, Oslo, Norway; **Kern*,[+]**—Integrated Climate Data Center, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Germany; **Aaboe[+]**—Research and Development Department, Norwegian Meteorological Institute, Tromsø, Norway; **Derby**—Global Cryosphere Watch Project Office, World Meteorological Organization, Geneva, Switzerland; **Dybkjaer**—Research and Development, Danish Meteorological Institute, Copenhagen, Denmark; **Garric[+]**—Mercator Ocean International, Toulouse, France; **Heil[+]**—Australian Antarctic Division and Australian Antarctic Program Partnership, University of Tasmania, Hobart, Tasmania, Australia; **Hendricks[+] and Rabe[+]**—Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung, Bremerhaven, Germany; **Holfort**—Bundesamt für Seeschifffahrt und Hydrographie, Rostock, Germany; **Howell[+]**—Climate Research Division, Environment and Climate Change Canada, Toronto, Canada; **Key[+]**—National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration, Madison, Wisconsin; **Lieser[+]**—Bureau of Meteorology, and Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia; **Maksym[+]**—Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; **Maslowski[+]**—Naval Postgraduate School, Monterey, California; **Meier[+]**—National Snow and Ice Data Center, CIRES, University of Colorado Boulder, Boulder, Colorado; **Muñoz-Sabater,[+] Nicolas,[+] and de Rosnay[+]**—European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom; **Özsoy[+]**—Polar Research Institute, TUBITAK Marmara Research Center, Maritime Faculty, Istanbul Technical University, Istanbul, Turkey; **Rack[+]**—Gateway Antarctica, School for Earth and Environment, University of Canterbury, Christchurch, New Zealand; **Raphael[+]**—Department of Geography, University of California, Los Angeles, Los Angeles, California; **Smolyanitsky[+]**—Arctic and Antarctic Research Institute, St. Petersburg, Russia; **Tietsche[+]**—European Centre for Medium-Range Weather Forecasts, Bonn, Germany; **Ukita[+]**—Faculty of Science, Niigata University, Niigata, Japan; **Vichi[+]**—Department of Oceanography, and Marine and Antarctic Research Centre for Innovation and Sustainability, University of Cape Town, Rondebosch, South Africa; **Wagner[+]**—Norwegian Ice Service, Norwegian Meteorological Institute, Tromsø, Norway; **Willmes[+]**—Earth Observation and Climate Processes, Trier University, Trier, Germany; **Zhao[+]**—School of Geospatial Engineering and Science, Sun Yat-Sen University, Zhuhai, China
* TL and SK are co-first authors and contributed equally to this work.

[+] **ORCID:** Lavergne—0000-0002-9498-4551; Kern—0000-0001-7281-3746; Aaboe—0000-0002-5618-4537; Garric—0000-0002-5385-710X; Heil—0000-0003-2078-0342; Hendricks—0000-0002-1412-3146; Howell—0000-0002-4848-9867; Key—0000-0001-6109-3050; Lieser—0000-0001-6870-1311; Maksym—0000-0003-3164-1882; Maslowski—0000-0002-5790-9229; Meier—0000-0003-2857-0550; Muñoz-Sabater—0000-0002-5997-290X; Nicolas—0000-0003-0518-100X; Özsoy—0000-0003-4320-1796; Rabe—0000-0001-5794-9856; Rack—0000-0003-2447-377X; Raphael—0000-0003-3199-942; de Rosnay—0000-0002-7374-3820; Smolyanitsky—0000-0002-8087-0393; Tietsche—0000-0002-2961-0289; Ukita—0000-0001-6461-179X; Vichi—0000-0002-0686-9634; Wagner—0000-0001-5268-4510; Willmes—0000-0002-2710-0699; Zhao—0000-0003-2274-891X

Climate observations underpin climate science and climate services and feed into policies for adaptation and mitigation. They inform the general public about the past and present state of our climate. Given the complexity of the climate system, a state-of-the-art global observing system is required to monitor the changes occurring on land, in the ocean, and in the atmosphere. To detect change over multidecadal time scales requires the interplay of many observation techniques, including in situ, satellites, proxies, and their synthesis in climate reanalyses. All these need to be carried out in a sustained and coordinated global climate observing system.

The Global Climate Observing System (GCOS) was established in 1992. It is a program initiated by the World Meteorological Organization (WMO) and cosponsored by WMO, the

Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme (UNEP), and the International Science Council (ISC). GCOS regularly reviews the status of the required monitoring system and produces guidance for its improvement. Status and guidance are given in documents including the Adequacy Reports (in 1998, 2003), Implementation Plans (in 2004, 2010, 2016), and Progress Reports (in 2009, 2015, 2021). At the time of writing, the current Implementation Plan is from 2016 (GCOS 2016) and a new one is in preparation for release in 2022. GCOS reports to the United Nations Framework Convention on Climate Change (UNFCCC) in Workstream "Systematic Observations" and regularly reports to the Subsidiary Body for Scientific and Technological Advice (SBSTA). GCOS is directly involved in the process of the UNFCCC and Conference of the Parties (COP; https://gcos.wmo.int/en/about/UNFCCC).

One of the key concepts introduced and promoted by GCOS is that of Essential Climate Variables (ECVs; Bojinski et al. 2014). An ECV is a physical, chemical or biological variable—or group of linked variables—that critically contributes to the characterization of the Earth's climate. Notably, ECVs need to be *relevant* (as a matter of fact, *essential*), *feasible*, and *cost effective* to monitor. They must make a critical impact as a UNFCCC Systematic Observation (essential and relevant), be measurable globally with existing technologies (feasible), and at an affordable level of investment (cost effective). GCOS currently defines 54 ECVs (https://gcos.wmo.int/en/essential-climate-variables). GCOS ECVs come with requirements, guidance, and best practices for the generation of high-quality Climate Data Records (CDRs). The GCOS requirements are data characteristics that must be met by CDRs (in terms of spatial and temporal resolution, accuracy, stability, etc.) to ensure their fitness for purpose. Funding and implementation agencies external to GCOS use the ECVs and their requirements as targets for their research and development and operational monitoring activities. The interplay between the GCOS ECVs and the implementation agencies is paramount to the development and sustainability of the global observing system. The ECV Inventory (https://climatemonitoring.info/ecvinventory/), maintained by space agencies, holds information on existing and planned satellite-based CDRs addressing the ECVs.

GCOS has at present one ECV, the sea ice ECV, to encapsulate all aspects of the sea ice environment. This ECV is under the umbrella of the Ocean Observations Physics and Climate Panel (OOPC), which is responsible for maintaining and evolving the definitions and requirements of all 19 Ocean ECVs. Linked to the Ocean ECVs are the Global Ocean Observing System (GOOS) Essential Ocean Variables (EOV; see www.goosocean.org/eov). The EOV concept was introduced in the Framework for Ocean Observing (Lindstrom et al. 2012) and covers not only climate but also ocean health and operational oceanography aspects. GOOS is the designated steward for GCOS Ocean ECVs, including sea ice. Since July 2020, the Global Cryosphere Watch (GCW), a body of WMO specialized in all aspects of the cryosphere, is a co-steward of the sea ice ECV.

Sea ice is a key component of the climate system and a headline indicator of climate change. It is also a very multivariate environment with processes unfolding at a wide range of spatial and temporal scales. Long-term, stable, and error-characterized CDRs of the sea ice environment are required for key applications such as monitoring climate change at global (Comiso et al. 2017b; Parkinson 2019; Trewin et al. 2021) and local scale (Cooley et al. 2020), evaluating climate simulations (Notz and SIMIP Community 2020; Roach et al. 2020; Davy and Outten 2020), providing input and boundary conditions to reanalyses (Hersbach et al. 2020; Lellouche et al. 2021), or combined model- and data-driven inference about future Arctic climate (Notz and Stroeve 2016). Because of the harshness and remoteness of the polar regions, sea ice CDRs rely mainly upon satellite Earth observation data, supported by a limited but indispensable set of in situ observations (such as buoys, moorings, submarine and ship expeditions, and flight campaigns).

Our main motivation for this contribution—a call for a revision of the current single-ECV model that suboptimally implements the multivariate sea ice environment—is backed up well by the community needs to improve the monitoring of polar regions for mitigation and adaptation measures and the continued advances in satellite Earth observation technologies and methodologies during the last decade. A new structure for the ECV will increase its visibility, renew the interest of the agencies involved in its monitoring, and ultimately attract the required funding for the climate science community to prepare, quality-control, and exploit new CDRs. This work was presented at the 29th GCOS Steering Committee meeting in December 2021.

Our paper is structured as follows. We introduce the complex sea ice environment and a set of key variables to describe it. Then, we recall how this environment is implemented in the GCOS sea ice ECV today, and what challenges this brings. Next, we outline a possible future structure to better serve the sea ice variables in GCOS. Discussion and outlook are then presented, and followed by our conclusions. Throughout this manuscript, we adopt the terminology used by GCOS (ECV, ECV product, CDR, etc.). The reader is referred to appendix A for a definition of these terms.

The sea ice environment

Sea ice forms from seawater at the interface between the ocean and the atmosphere. Its formation plays a key role for vertical exchange of salt and heat within the upper ocean and for the global thermohaline circulation, and its melt influences near-surface stratification of the polar and surrounding seas (Comiso 2010; Thomas 2016). It extends between 16 and 28 million km^2 globally year-round (Parkinson and DiGirolamo 2021). During the past 40 years, the sea ice environment has undergone massive changes. In the Arctic, sea ice has been shrinking in coverage and thickness (Comiso et al. 2003, 2017b; Stroeve and Notz 2018; Kwok 2018) and has become younger (Kwok 2018; Tschudi et al. 2020) and more mobile (Rampal et al. 2009; Kwok et al. 2013; Spreen et al. 2020). These changes coincide with an earlier onset of an extended summer melt period (Stroeve et al. 2014), which is in turn associated with an overall reduced snow depth on sea ice (Webster et al. 2014, 2018). Altogether, this has implications for the net radiation balance, and the heat, momentum, and matter fluxes at the ocean–atmosphere interface with consequences for, e.g., the ocean stratification (Timmermans and Marshall 2020) and near-surface air temperatures and related biogeochemical processes (Bhatt et al. 2021; Lannuzel et al. 2020) in the Arctic and for midlatitude weather (Cohen et al. 2020). On the one hand, these changes can be beneficial for marine transportation and related socioeconomic activities (Melia et al. 2016; Li et al. 2021; Mudryk et al. 2021). On the other hand, less sea ice, and especially less landfast sea ice, results in wave-induced undercutting of permafrost, leading to increased coastal erosion (Barnhart et al. 2016; Liew et al. 2020) and affects human activities relying on landfast sea ice coverage (Cooley et al. 2020). Regional changes in sea ice cover characteristics affect, e.g., the amount and seasonality of primary production (Ardyna and Arrigo 2020; Zhuang et al. 2021) and ocean–atmosphere gas exchanges (Lannuzel et al. 2020), prey–predator relationships (Divoky et al. 2021), and fisheries (Huntington et al. 2020; Fauchald et al. 2021).

The signs of changes in the Antarctic sea ice environment are more complex and uncertain than in the Arctic. Its coverage is highly variable (Comiso et al. 2017a; Parkinson 2019) with substantial long-term regional changes, particularly in the Bellingshausen Sea, Amundsen Sea, and Ross Sea (Stroeve et al. 2016; Hobbs et al. 2016; Comiso et al. 2017a). The observational record of Antarctic sea ice thickness is less mature than in the Arctic and trends in the thickness record remain inconclusive overall (Worby et al. 2008; Kurtz and Markus 2012; Li et al. 2018; Wang et al. 2020). Haumann et al. (2016) suggested thinning in the Bellingshausen Sea and Amundsen Sea, and thickening in parts of the Weddell Sea and western Ross Sea during 1992–2008, but their analysis did not include the unprecedented dip in sea ice area during the last 5 years (Parkinson and DiGirolamo 2021; Turner et al. 2020). The observed regional changes in the Antarctic sea ice cover affect the Southern Ocean ecology, for example, open ocean primary production (Biggs et al. 2019; Jena and Pillai 2020; Schultz et al. 2021), krill and their predators (Atkinson et al. 2019; Hückstädt et al. 2020; David et al. 2021), and ocean–atmosphere gas and matter exchange (Brown et al. 2019; Schultz et al. 2021; Brean et al. 2021). Regional thinning and reduction of the Antarctic sea ice cover affect ice shelves and glaciers—particularly in the western Antarctic—due to reduced buttressing against ocean swell and wind waves (Massom et al. 2010, 2015; Ardhuin et al. 2020). Concurrent changes in iceberg calving and stability of Antarctic landfast sea ice impact formation of coastal polynyas and associated ice production (Drucker et al. 2011; Nihashi and Ohshima 2015; Tamura et al. 2016; Fraser et al. 2019), which feed back to deep water formation of global relevance (Ohshima et al. 2013; Kitade et al. 2014; Kusahara et al. 2017), coastal primary production (Arrigo et al. 2015), and on the water masses entering cavities underneath the ice shelves (Shepherd et al. 2018).

Sea ice crucially affects the efficiency of exchange processes at and across the ocean–atmosphere interface, e.g., the net surface shortwave and longwave radiation balance. In this context, the sea ice concentration is essential to know since the surface albedo of ice differs from that of the open ocean. Because the sea ice albedo varies with the surface type (from about 0.12 for very thin ice over 0.55 for bare first-year ice to about 0.87 for freshly fallen snow; Perovich 1996; Zatko and Warren 2015), it is crucial to know how it partitions across the area of known sea ice. For example, the fraction of bare sea ice versus that of melt ponds is critical.[1] Sea ice also fundamentally reduces the amount of solar radiation available for heating the ocean and the amount of light available for the marine biological production during summer. The transmission of solar radiation into the water column underneath the ice cover depends primarily on sea ice thickness and snow depth (Nicolaus et al. 2010; Katlein et al. 2015) while the fraction and depth of melt ponds and sea ice age also play a role. Deriving the net surface shortwave radiation balance correctly (reflection and transmission) thus requires at least the five sea ice variables sea ice concentration, thickness, and age as well as surface albedo and snow depth on sea ice. Together with the sea ice concentration determining the contribution of the open water, the ice surface temperature is the sole parameter determining the upwelling longwave radiation at the surface, being a key parameter of Arctic surface climate (Graham et al. 2019). The increase of the ice surface temperature concurrent with a thinner, younger sea ice cover with less deep snow (Box et al. 2019) contributes to temperatures in the Arctic rising twice as fast as in the Northern Hemisphere as a whole (Stroeve and Notz 2018). Through its relation to air temperatures near the surface and their horizontal and vertical gradients, the ice surface temperature influences cyclogenesis and cyclolysis, particularly during winter, with potential impact beyond the high latitudes (Cohen et al. 2020).

Sea ice moves laterally at the ocean–atmosphere interface. A substantial fraction of the sea ice mass that forms during the winter season melts far away from its origin area. For instance, the sea ice mass transport through Fram Strait constitutes between one-third and one-half of the freshwater export out of the Arctic Ocean at this gate (Haine et al. 2015) and between 10% and 15% of the total Arctic Ocean sea ice volume (Spreen et al. 2020). Such large redistribution of sea ice changes the upper-ocean stratification substantially, with salinity excess at the location of ice formation and contribution of freshwater at the melting location, and triggers oceanic processes (Karcher et al. 2005; Haumann et al. 2016). It is, therefore, important to monitor this large-scale sea ice mass transport, for example, in the Weddell Sea and Ross Sea, and through Fram Strait. To quantify the freshwater volume transport related to sea ice requires information of at least sea ice drift, sea ice concentration, and thickness (the latter two combined into sea ice volume), as well as density (to estimate sea ice mass). On the microscale, sea ice density can indirectly be estimated from sea ice age, a proxy for the presence of air bubbles and brine concentration that both drastically change through the first summer melt season a sea ice parcel survives (Vant et al. 1974; Tucker et al. 1992); on the macroscale sea ice density is a function of the ice/water volume distribution of deformed ice.

[1] Melt ponds form on top of sea ice (so far predominantly in the Arctic) as the result of summer melt. Their areal fraction on sea ice and their depth vary with sea ice age, snow depth, and surface topography among other things (Perovich et al. 2007).

To understand and predict past and future anomalies in the transported sea ice volume, it is important to investigate the history of a sea ice parcel between its formation and its export, e.g., out of the Arctic Ocean. The origin of a sea ice parcel can be tracked with backward trajectories, which requires knowledge of sea ice drift (Pfirman et al. 1997; Krumpen et al. 2016). Along these trajectories back in time, the sea ice likely changed in response to several local processes: thermodynamic and dynamic thickness changes (growth, melt, and deformation), and changes to the snow cover (accumulation, melt, and metamorphism). A comprehensive quantification of the changes an ice parcel underwent along its trajectory therefore requires in addition information about the ice and snow surface temperature and surface albedo.

To summarize, sea ice is a complex environment characterized by a large number of geophysical variables. These enter many processes and interactions with the rest of the climate system. After careful considerations—using notably proxy variables—we select a core set of seven geophysical variables that are critical to monitor: sea ice concentration, sea ice thickness, snow depth, albedo and its surface partition,[2] surface temperature, sea ice age, and sea ice drift (Table 1). These are individually and collectively key indicators of climate change, with contrasted signals across the two hemispheres and regions within.

[2] By surface partition we refer to the subgridscale distribution of the albedo of different surface types, such as snow covered or bare ice, melting ice, different forms of melt ponds, and different forms of young and thin ice.

The GCOS sea ice ECV in 2021 and its challenges

In the current Implementation Plan (IP-2016; GCOS 2016), the sea ice ECV is the only ECV concerned with all aspects of the sea ice environment. This ECV holds four variables (a.k.a. ECV products, see appendix A): sea ice concentration, edge/extent, thickness, and drift. Compared to those discussed in the previous section, it is clear that some critical variables are today missing from GCOS monitoring plans. However, before considering if more ECV products should be added to the sea ice ECV, we must discuss if the current single-ECV structure serves its purpose well. We argue that this is not the case.

A first challenge with the current single-ECV model impacts one of GCOS's core activities: to regularly assess the status of the global observing system to uncover where progress was made and where more efforts are needed. This process is implemented through the intertwined cycles of Implementation Plans and Status Reports roughly every 5 years. The sea ice ECV is

Table 1. Overview of names, short descriptions, main determining processes, and areas of relevance and impact of the core set of seven sea ice variables.

Name and acronym	Description	Is determined by	Is relevant for/impacts
Sea ice concentration (SIC)	Fraction of known ocean area covered by sea ice	Ice formation and melt, dynamic processes, SID, SIT	Sea ice area and extent, sea ice mass, net short- and longwave flux
Sea ice thickness (SIT)	Vertical extent of the sea ice	Thermodynamic growth and melt, dynamic processes, SID, SND	Sea ice mass, ISA, IST, SID
Snow depth (SND)	Vertical extent of the snow on top of the sea ice	Snow precipitation and redistribution, ice surface accumulation ability, metamorphism and melt, SIC, SIT, IST, ISA, AGE	SIT and sea ice mass, ISA, IST
Ice surface albedo (ISA)	Sea ice and snow surfaces' ability to reflect solar shortwave radiation	Sea ice growth, melt and aging, snowfall, metamorphism and melt, SND, SIT, AGE	Net shortwave surface radiation balance, sea ice mass, area and extent
Ice surface temperature (IST)	Ice or snow surface temperature	Sea ice growth, melt and aging, snowfall, metamorphism and melt, SND, SIT, AGE	Net longwave surface radiation balance, physics of sea ice processes, sea ice mass, area and extent
Sea ice age (AGE)	Lifetime of the sea ice since its formation	Thermodynamic processes, drift and dynamic processes, SIT, SND, SID	Sea ice mass, ice-type fraction and distribution
Sea ice drift (SID)	Lateral movement of the sea ice (transport and deformation)	Surface wind stress, bottom ocean current stress, sea ice surface and bottom topography, SIC, SIT	SIT distribution, SIC, AGE, sea ice surface topography, sea ice bottom topography

an umbrella for widely different geophysical variables. With their different maturity levels, it becomes difficult to assign a single status score (from 1: Poor to 5: Very Good) in terms of "Adequacy of the Observational System and Availability and Stewardship" (see Table 1 in GCOS 2021). The single-ECV model, leading to a single assessment score, hides the variety of actual statuses of the four geophysical variables and limits the usefulness of the report.

The same applies for planning GCOS Actions to improve the systems of observations sustaining the ECVs in the Implementation Plan. A striking example is "Action O35: Satellite sea ice" which aims at ensuring the adequacy of the satellite-based observing system for the four ECV products although these require very different satellite technologies. In GCOS (2021, Table 9, Status of Implementation Plan Ocean Actions), the status of this action is given a score of 4 ("progress on track"), but an extended comment in appendix B details the answer into the different variables and their required satellite missions, noting that *the score depends heavily on which ECV Product is considered*. The final score is indeed described as a mix of 4 ("progress on track") for sea ice concentration and drift at coarse resolution, 3 ("underway with significant progress") for the same variables at higher resolution, and 2 ("started but little progress") for sea ice thickness (noting the potential imminent gap in availability of polar altimetry missions). Since the overall score of 4 is the only one reported in the main body of the report, it is clear that the single-ECV model is suboptimal for following progress and plan actions really needed for this ECV.

Another negative consequence of the single-ECV model is to slow the development of CDRs for the four ECV products. In GCOS (2016), GCOS estimates an annual cost for generating satellite-based CDRs to US$1–10 million for each ECV (see, e.g., Action O35 for sea ice, O36 for ocean color, O8 for sea surface temperature, etc.). In essence, these actions strengthen the concept of a "funding unit per ECV." Compared to ECVs consisting of one or two geophysical variables, ECVs that are umbrellas for different variables have to spread their "funding unit" across more CDRs, especially if they require very different Earth observation techniques. As a result they lose traction and make slower progress toward fulfilling the GCOS requirements.

Finally, it is interesting to look back at the evolution of the sea ice ECV throughout the history of GCOS (Fig. 1). When GCOS developed its first implementation phase, in the early 1990s, satellite remote sensing of sea ice concentration and extent were already well established owing to the decade long time series of passive microwave missions. This was reflected in the first "satellite supplement" (GCOS 2006) to the first Implementation Plan (GIP; GCOS 2004) that defined only one ECV product for the ECV (O.1 Sea Ice Concentration). Sea ice

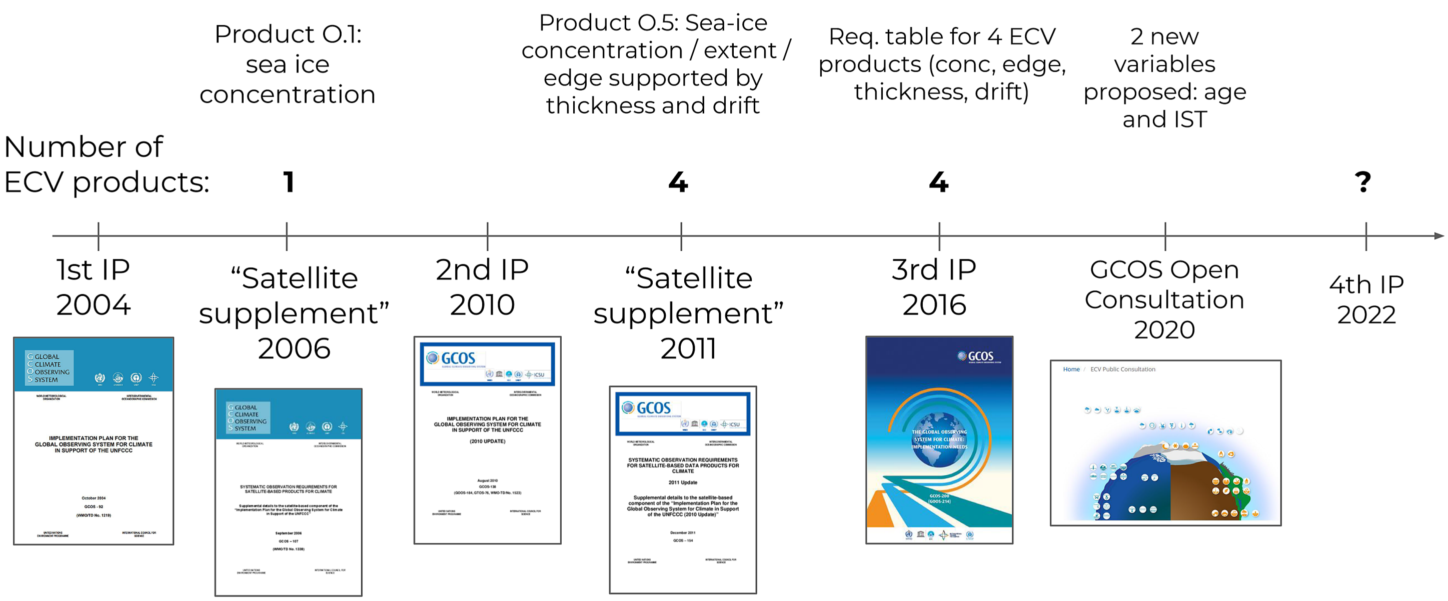

Fig. 1. Evolution of the definition and content of the sea ice ECV, particularly in terms of ECV products, through several GCOS reports.

thickness and drift retrievals were mentioned as supporting variables, lacking mature-enough observation capabilities. With the availability of dedicated cryosphere and polar missions (including *CryoSat-2*, *ICESat*, RADARSAT), the satellite supplement GCOS (2011) to the second Implementation Plan (IP-10; GCOS 2010) defined the four ECV products we have today. This was not modified by the third Implementation Plan (GCOS 2016). This brief history of the sea ice ECV highlights how the new geophysical variables—that were deemed critical and whose observation systems had become sufficiently mature for today's needs—were added *into* the existing ECV (as additional ECV products) instead of *to the side* (initiating new ECVs). Today's suboptimal situation is a direct consequence of this choice.

A new structure for the sea ice ECV

As seen in the section "The sea ice environment," sea ice is a complex environment that demands a core set of geophysical variables to describe its state in terms of mass, dynamics, and interactions with the ocean and atmosphere. The four ECV products considered in the GCOS plans since 2010 are not enough.

Owing to technological developments and the dedication of the space agencies and of the research community, the set of Earth observation techniques needed to generate CDRs for the core variables introduced in "The sea ice environment" is now available (see also Fig. 2).

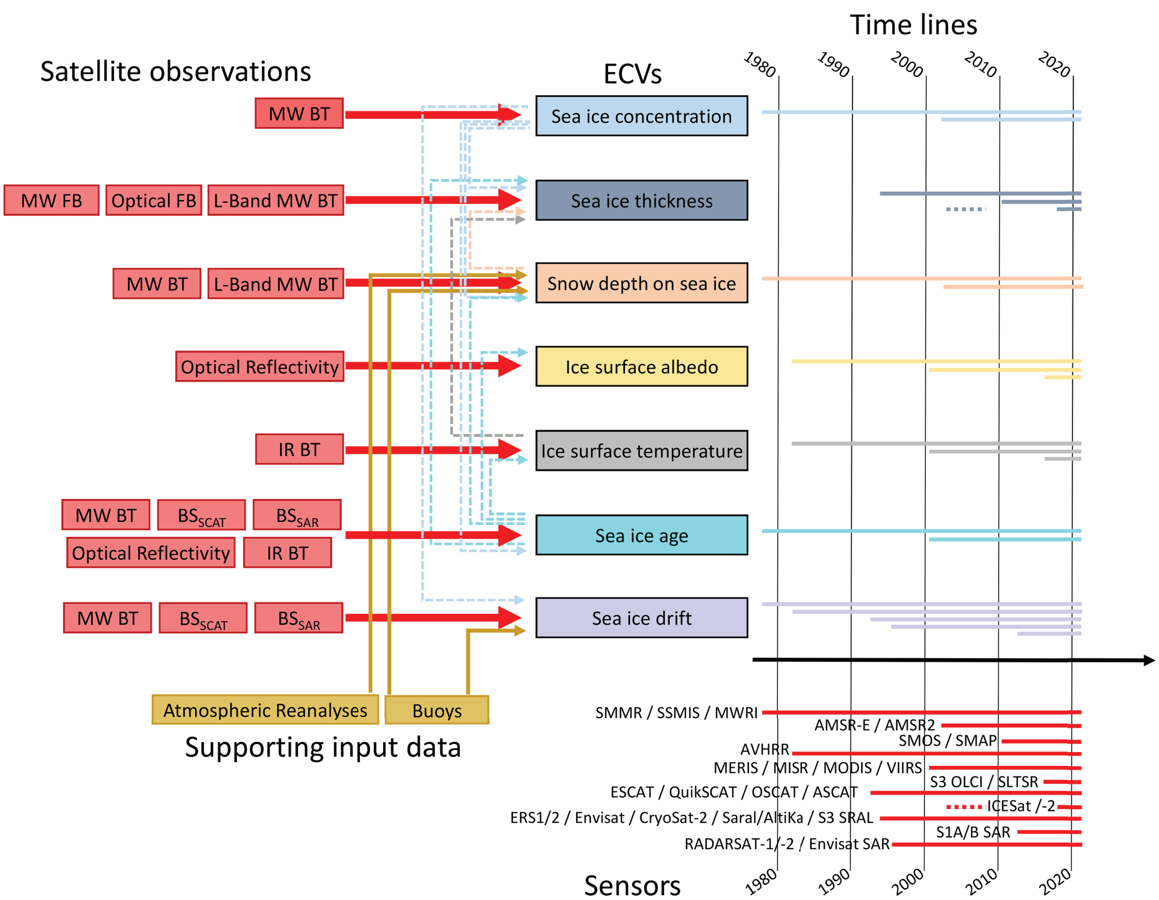

Fig. 2. Overview of the seven ECVs and their potential temporal coverage based on available satellite observations. On the left side we display input satellite observations: MW = microwave, FB = freeboard, BT = brightness temperature, BS = backscatter, IR = infrared, SCAT = scatterometer, SAR = synthetic aperture radar. The middle column denotes the ECVs with two kinds of supporting data required given at the bottom. On the right side we provide the time lines for which the derivation of CDRs and data products for these ECVs has been demonstrated. Several time lines may exist per ECV denoting CDRs derived from different satellite sensors. These sensors and their time lines (in red) we provide at the bottom right. The dotted time line for one of the sea ice thickness products is for *ICESat* providing discontinuous coverage; all other products are continuous as far as allowed by their retrieval.

Sea ice concentration (SIC) has been derived continuously from satellite microwave brightness temperature observations since October 1978 for both hemispheres at (mostly) daily temporal resolution. A large set of different algorithms to derive SIC from brightness temperature observations exists (Ivanova et al. 2015). SIC CDRs are the backbone of today's knowledge about sea ice area and extent and their long-term trends. Several SIC CDRs are supported by operational programs (Lavergne et al. 2019; Peng et al. 2013) and are extended with interim CDRs. Developments toward alternative methodologies and input observations, e.g., optical/infrared or synthetic aperture radar exist (Komarov and Buehner 2021; Ludwig et al. 2020). SIC (CDR) evaluation is at a reasonably mature stage (Kern et al. 2019, 2020).

Sea ice thickness (SIT) has been derived from satellite radar altimeter freeboard observations since March 2002 for both hemispheres (e.g., Sallila et al. 2019; Tilling et al. 2019; Paul et al. 2018). For the Arctic, attempts extend back to 1993 (Laxon et al. 2003). Alternative SIT data products derived from satellite laser altimeter freeboard observations exist for both hemispheres based on *ICESat* (Kwok et al. 2009; Kern et al. 2016) since February 2003 (with data gaps) and on *ICESat-2* (Kwok et al. 2021; Kacimi and Kwok 2020) since October 2018. Most altimeter-based SIT CDRs have a monthly temporal resolution. SIT data products based on satellite brightness temperature observations at L band extend back to 2010 but are limited in their maximum retrievable SIT value (Tian-Kunze et al. 2014). They offer daily temporal resolution and better accuracy for thin ice (Ricker et al. 2017). SIT data products based on empirical relations to ice surface temperature observations allow expanding the time series back to 1982 (Key et al. 2016; Mäkynen and Karvonen 2017). The maturity of SIT CDRs is better for Arctic than Antarctic sea ice (Paul et al. 2018) and for more recent than older altimeters (Tilling et al. 2019). So far, SIT CDRs of the Arctic have been limited to the winter season.

Snow depth on sea ice (SND) has been derived from satellite brightness temperature observations at daily temporal resolution for both hemispheres since 1978 (Markus and Cavalieri 1998; Brucker and Markus 2013). The corresponding CDRs can contain regional biases caused by the retrieval method being sensitive to sea ice age, sea ice roughness, and snow properties. Several alternative algorithms aiming to mitigate these biases have been developed for more recent satellite missions in the Arctic (Maaß et al. 2013; Rostosky et al. 2018; Braakmann-Folgmann and Donlon 2019) and Antarctic (Markus et al. 2011; Kern and Ozsoy 2019). Using dual-frequency radar or combined radar–laser altimeter freeboard observations is attempted (Guerreiro et al. 2016; Lawrence et al. 2018; Kwok et al. 2020), as is the combination of brightness temperature observations with radar altimetry (Xu et al. 2017). These alternative solutions had so far the drawback of a monthly temporal resolution and considerably shorter temporal coverage. At present, a promising avenue is using atmospheric reanalyses informed by in situ, airborne, and satellite observations (Liston et al. 2020; Stroeve et al. 2020). Zhou et al. (2021) presented a first intercomparison of SND retrieval methods for the Arctic.

Ice surface albedo (ISA) has been derived since 1982 from observations in the optical frequency range with a number of satellite sensors at daily (with data gaps) or monthly temporal resolution (Istomina et al. 2020; Peng et al. 2018; Kharbouche and Muller 2018; Zhou et al. 2019; Pohl et al. 2020). Cloud cover is a limiting factor and current techniques for cloud masking are not tailored sufficiently well for the polar regions. Attempts using brightness temperature observations exist (Laine et al. 2014). The ISA is more heterogeneous during summer because of the larger number of surface types with different albedo (e.g., melt ponds), and also at the subpixel scale. In the Arctic, data products of the melt-pond fraction on top of the sea ice have been retrieved since summer 2000 at daily to weekly temporal resolution (Rösel and Kaleschke 2012; Zege et al. 2015; Istomina et al. 2020; Lee et al. 2020). Such data products allow partitioning of the ISA by surface type, and to assess summertime sea ice concentration retrieval from brightness temperature observations (Kern et al. 2020).

Sea ice (and snow) surface temperature (IST) CDRs can be based on two methodologies. The first kind utilizes satellite infrared temperature observations since 1982 at daily (with data gaps) to monthly temporal resolution (Key and Haefliger 1992; Kang et al. 2014; Dybkjaer et al. 2018; Key et al. 2016; Liu et al. 2018). These are a measure of the actual physical temperature of the top surface, be it bare ice or the top of the snow. While clouds are an uncertainty source similar to for ISA CDRs, existing IST CDRs are more mature thanks to substantial evaluation efforts (Theocharous and Fox 2015; Høyer et al. 2017; Fan et al. 2020). CDRs harmonized across different satellite sensors exist (Dodd et al. 2019; Høyer et al. 2019; Karlsson et al. 2017). The second kind of IST CDRs is based on satellite microwave brightness temperature observations since June 2002 at daily temporal resolution (Lee and Sohn 2015; Comiso et al. 2003, 2017a; Lee et al. 2018; Kilic et al. 2019). These are a measure of the ice–snow interface (or ice-surface temperature in case of bare ice) and are considerably less sensitive to clouds.

Sea ice age (AGE) CDRs rely mainly on two Earth observation techniques. The first technique utilizes sea ice drift and concentration CDRs to track virtual ice parcels. Only one such CDR exists and it is limited to the central Arctic (Tschudi et al. 2020). Methodological improvements have been identified (Korosov et al. 2018). The second technique uses large-scale brightness temperature and/or backscatter observations and classifies the sea ice cover into age categories[3] (e.g., first-year ice, multiyear ice, more rarely second-year ice) (Cavalieri et al. 1984; Swan and Long 2012; Lindell and Long 2016; Ye et al. 2016; Lee et al. 2017). The first approach offers better accuracy in the temporal domain—age scalar versus category—and year-round availability, while the second approach yields finer spatial resolution. AGE CDRs document the decrease of old (generally thicker) sea ice in the Arctic beyond what is possible with current sea ice thickness products (Maslanik et al. 2011; Tschudi et al. 2020; Liu et al. 2020). CDRs of AGE do not yet exist for the Antarctic.

[3] These products are sometimes called sea ice *type* data products, but what they really measure is the sea ice age.

Sea ice drift (SID) CDRs have been derived in the form of large-scale sea ice motion fields from satellite brightness temperature and backscatter observations merged with optical imagery for both hemispheres at (mostly) daily temporal resolution since October 1978 (Kwok et al. 1998; Girard-Ardhuin and Ezraty 2012; Tschudi et al. 2020), informed in the Arctic by buoy drift and atmospheric reanalyses. Results from numerous applications and evaluations (Schwegmann et al. 2011; Sumata et al. 2014, 2015; Haumann et al. 2016) are in line with suggested methodological improvements (Kwok 2008; Lavergne et al. 2010). SID data products based on synthetic aperture radar backscatter observations exhibit a substantially finer spatial resolution (Kwok et al. 1990; Komarov and Barber 2014; Muckenhuber and Sandven 2017). They have for a long time been used successfully to retrieve parameters describing forms and impact of sea ice deformation, i.e., linear kinematic features such as ridges or leads (Kwok et al. 1995; Hutter et al. 2019; Rampal et al. 2019). The spatiotemporal coverage with high-resolution synthetic aperture radar backscatter observations has substantially improved during the last decade in both hemispheres and is expected to further increase.

It should be clear from the list above, and from Fig. 2, that the core variables require different Earth observation methodologies, although some overlap exists. Different methodologies mean that different expert communities must engage to improve the algorithms and prepare better CDRs. A nonexhaustive list of challenges and required Research and Development efforts for each variable is compiled in appendix B.

The seven core sea ice variables we introduced in "The sea ice environment" section are thus *relevant* and essential, and sustained by *feasible* and *cost-effective* observation systems relying heavily on existing satellite Earth observation systems. By fulfilling these three conditions, the seven variables qualify for becoming GCOS ECVs in their own right.

We indeed advise against making them new ECV products of the existing sea ice ECV for all the reasons outlined in the section "The GCOS sea ice ECV in 2021 and its challenges." We rather argue that the current sea ice ECV should be dismantled, and that seven sea ice related ECVs are initiated. The seven ECVs are sea ice concentration, sea ice thickness, snow depth on sea ice, sea ice surface temperature, sea ice albedo and its surface partition, sea ice age, and sea ice drift. These seven ECVs would ideally be organized in a ocean cryosphere cluster within the ocean ECVs, similarly to how a cryosphere cluster holds the glaciers, permafrost, ice sheets, and snow ECVs within the terrestrial domain of GCOS.

With respect to the four sea ice variables currently implemented by GCOS as ECV products, this means pursuing the efforts on sea ice concentration, thickness, and drift, and introducing snow depth, surface temperature, albedo, and sea ice age. We consider that today's "sea ice edge/extent" ECV product (a binary ice/no-ice information) can be folded into the new sea ice concentration ECV. Sea ice extent and area, key indicators of climate change derived from the sea ice concentration ECV, are not required as ECVs or ECV products.

Discussion and outlook

To introduce seven independent sea ice related ECVs in GCOS will undoubtedly at first be perceived as a jump with respect to today's single-ECV model. At the same time, seven geophysical variables represent less than a doubling with respect to the four ECV products we have today, a number that has remained unchanged since 2011 despite the many advances in satellite Earth observation technologies. The question is really one of organizing the sea ice variables to best serve GCOS missions. To keep the seven variables as ECV products of the existing sea ice ECV is not a viable option and would further exacerbate the challenges to maintain and develop observations of this critical domain of the climate system.

In addition to the arguments from "The GCOS Sea Ice ECV in 2021 and its challenges," we note that, should the current single-ECV model be continued with seven ECV products, it would present a stark contrast with what is practiced for other domains covered by GCOS. For example, making the correspondence between variables describing the sea surface on the one hand, and those describing the sea ice on the other hand (motion: ocean currents versus sea ice drift, temperature: sea surface temperature versus ice surface temperature, shortwave radiation: ocean color versus sea ice albedo, vertical dimension: sea level versus sea ice thickness, etc.) we see that all the surface ocean variables are ECVs, while the sea ice variables would be ECV products.

In GCOS (2016), no ECV has seven ECV products. Only 25% ECVs have four or more ECV products, and 41% contain a single ECV product. When an ECV holds more than one ECV product, it is often the same geophysical variable but with different requirements. Examples are the Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) ECV that has two ECV products, one for modeling (required spatial resolution 200–500 m) and one for adaptation (50 m), and similarly for the albedo, leaf area index, and land cover ECVs. With respect to other ECVs, a sea ice ECV with seven ECV products would thus have a record large number of ECV products, corresponding to distinct geophysical variables requiring different Earth observation technologies. Other ECVs (e.g., on ice sheets and shelves, on glaciers, on cloud properties, on lakes) are in a similar situation to the sea ice ECV. The present work can be an inspiration for these communities to propose a revision of their ECVs.

By contrast, introducing these seven geophysical variables as ECVs in their own right would close important gaps in global coverage of today's GCOS ECVs. For example, GCOS defines already five ECVs dedicated to temperature: for the near-surface air, the upper air, the land surface, the ocean surface, and its interior (subsurface). The new sea ice surface temperature ECV would fill the coverage gap in the polar regions. By the same token, GCOS has an albedo ECV for all land surfaces, but not for sea ice. Unsurprisingly, Action T38[4] "Improve quality of snow (ice and sea ice) albedo products" was recently reported

[4] The "T" here stands for "terrestrial" since the albedo ECV is only for land surfaces.

as “2: Started but little progress” by GCOS (2021). It is timely to define the sea ice albedo ECV as a step toward addressing this action. The same argument can be made for snow depth on sea ice: defining a dedicated ECV will complement the snow ECV that today resides in the terrestrial domain of GCOS.

Regardless of their future organization within GCOS, the seven variables will require repeated cycles of research and development to improve their reliability, reduce the spread between existing CDRs, and in general achieve progress in maturity toward meeting their specific GCOS requirements. In addition to the specific research and development on the algorithms (see a selected list per variable in appendix B), the development of Fundamental Climate Data Records (FCDR) should be pursued (Fennig et al. 2020; Brodzik et al. 2018; Karlsson et al. 2017), including data rescue from the early satellite era. This will allow to fully exploit the satellite missions available for each variable (Fig. 2). A continued effort to collect, quality-control, and make available in situ observations of the sea ice environment should also continue to be a priority. Transparent intercomparison exercises of the CDRs and their algorithms should be conducted regularly for all variables to assess progress and improve confidence.

We finally recall that, although the focus of this paper has been on the individual geophysical ECVs and the preparation of mature and sustained CDRs, we also call for efforts to make these variables act together (and with ECVs from other domains) for a better monitoring of the polar regions in a changing climate. Key open questions such as 1) the freshwater budget of the Arctic including sea ice mass fluxes toward lower latitudes, 2) the coupling between sea ice, land ice, and freshwater in the Southern Ocean, 3) teleconnections between changes in Arctic sea ice cover and midlatitude weather, 4) coastal permafrost erosion and impact on infrastructures and communities, and 5) impact of sea ice retreat on primary production and ecosystems—to name just a few—require the individual long-term CDRs but also dedicated cross-ECV activities. A well-established tool to bring together as many CDRs as possible in a complete description of the global physical system is climate reanalysis, which will greatly benefit from the seven sea ice ECVs we call for here. All in all, the seven sea ice ECVs will bring forward a more consistent Earth system approach across the GCOS domains, in support to WMO’s strategic plan (WMO 2019).

Conclusions

We need long-term, error-characterized, and sustained observation systems of the atmosphere, land, and ocean to monitor climate change, inform societies, and adopt adaptation policies. The Global Climate Observing System (GCOS) was initiated by the World Meteorological Organization in the early 1990s to assess progress and guide development toward the required monitoring systems, using a set of ECVs as a key tool.

Sea ice is a key element of the climate system, both as an indicator of its evolution and a mechanism of changes in the polar regions, with implications at all latitudes. The sea ice environment (including its snow cover) is complex and the home for many processes and interactions. We selected a set of seven core variables whose observations are critical for the monitoring of the climate system. In contrast, a set of only four variables is identified by GCOS today as constituents of a single sea ice ECV (GCOS 2016).

In this contribution we showed how today’s umbrella model of one sea ice ECV is posing real challenges to GCOS and the community when it comes to defining and reporting on the status of the observation system. The single-ECV model is also shown to be a hinder to the development of mature and sustained CDRs when the concept of “one unit of funding per ECV” is applied. We also showed how the sea ice ECV started as a single well-defined variable (sea ice concentration) and how more variables were later added into it (as ECV products) and not to the side (as new ECVs).

We thus call for dismantling today’s sea ice ECV and for initiating a set of seven ECVs (sea ice concentration, sea ice thickness, snow depth on sea ice, sea ice surface temperature, sea ice albedo and its partition, sea ice age, and sea ice drift). This will permit a more complete monitoring of the sea ice environment and its interactions in the global climate system. All seven variables are essential, feasible, and cost effective and thus fully qualify as GCOS ECVs.

Furthermore, these seven ECVs much better reflect the many advances allowed by Earth observation satellites in the last decade. To organize the variables as ECVs (not ECV products) is key to avoid exacerbating the challenges with today's model, noting that the majority of GCOS ECVs have one or two ECV products today. The seven new ECVs will close critical coverage gaps in existing variables such as temperature, albedo, and snow. It will finally reconcile the treatment of sea ice variables with what is the practice in other domains of GCOS, e.g., the ocean surface ECVs.

Once the seven sea ice variables become ECVs, implementation and funding agencies will take on the challenge for renewed research and development efforts to further improve the algorithms and prepare more mature CDRs. A focus at first, the mature and sustained CDRs will later open many opportunities for cross-ECV activities (including with other spheres of the climate system) and ingestion into the future coupled climate reanalyses in support to WMO's Earth system approach strategy.

An upcoming opportunity for GCOS to revise its list of ECVs is the preparation of the next implementation plan (IP-2022). The sea ice community will look forward to assisting in that regard.

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Appendix A: Terminology

We recall here the terminology adopted by GCOS and that we use in this contribution. To help avoid confusion we also discuss the GCOS terminology and compare it to that used otherwise in the climate community.

Definitions. The definitions below are from GCOS (2016, appendix B) (the wording was shortened and adapted).

- An *Essential Climate Variable* (ECV) is a physical, chemical, or biological variable or group of linked variables that critically contributes to the characterization of the Earth's climate.
- The term *ECV product* denotes parameters that need to be measured for each ECV. For instance, the ECV cloud property includes at least five different geophysical variables where each of them constitutes an ECV product. An ECV holds at least one ECV product.
- A *Climate Data Record* (CDR) is a time series of measurements of sufficient length, consistency and continuity to determine climate variability and change.
- A *Fundamental Climate Data Record* (FCDR) is a CDR which consists of calibrated and quality-controlled sensor data. A CDR is often based on an FCDR.

Disambiguation. The terms used by GCOS might be interpreted differently by the climate community at large. We clarify below some frequent sources of confusion.

- ECVs can be variables (e.g., sea surface temperature ECV, albedo ECV) or concepts characterized by several variables (e.g., sea ice ECV, snow ECV).
- An ECV product is equivalent to a geophysical variable (e.g., sea surface temperature, albedo, sea ice thickness, snow water equivalent). An ECV holds at least one ECV product: the sea surface temperature ECV holds one ECV product (sea surface temperature) while the snow ECV holds two ECV products (snow area and snow water equivalent). Most ECVs hold one ECV product.
- Importantly, ECV products are not data products, but the CDRs are. Various data providers develop different CDRs that target the definition and requirements of an ECV product. There are thus often several CDRs for each ECV product.

Appendix B: Research needs for Earth observation monitoring of the seven sea ice variables

The section "A new structure for the sea ice ECV" presented a list of Earth observation techniques available for each of the seven core variables proposed as new ECVs. Although the satellite technologies and algorithms are mature enough to prepare fit-for-purpose CDRs, not all challenges have been solved and there is still the need for research and development efforts to improve the maturity of existing data products and CDRs. We provide here a nonexhaustive, nonprioritized list of such items requiring attention from the community and funding agencies.

1) Sea ice concentration (SIC): reduction of SIC bias and uncertainty during the summer melt period when liquid water coexists as openings and leads between the ice floes and as melt ponds on top of the ice floes, improvement of the spatial resolution, securing long-term intersensor consistency.
2) Sea ice thickness (SIT): hemisphere-specific reduction of retrieval uncertainties (freeboard, snow depth, densities, internal and ice–snow interface processes), moving away from using snow depth climatology, closure of retrieval gap in summer in the Arctic, extension to early altimeters, securing consistency across sensors, better exploitation of SIT proxies such as sea ice age, addressing possible future gap in polar altimetry and L-band radiometry missions.
3) Snow depth on sea ice (SND): better quantification and reduction of biases over deformed and old ice, and those due to snow wetness and other snow property variations, production and evaluation of additional snow depth CDRs for both hemispheres using innovative concepts that combine numerical models, in situ and various satellite observations, conduction of snow depth CDR intercomparison studies, open communication of remaining limitations and uncertainties.
4) Ice surface albedo (ISA): ISA CDR evaluation at gridscale and subgridscale level over all sea ice types, improvement of cloud mask to mitigate biases, harmonization of CDRs obtained from different satellites, harmonization and evaluation of melt-pond fraction data products.
5) Sea ice (and snow) surface temperature (IST): improvement of cloud mask to further mitigate biases in IST CDRs based on infrared temperature observations, continuation of their evaluation, evaluation of IST CDRs based on microwave brightness temperatures and their further exploration, taking advantage of infrared/microwave temperature observation synergies—for instance, in the form of time series analysis.

6) Sea ice age (AGE): reconcile the two main approaches (Lagrangian tracking, and age category mapping from brightness temperature and backscatter data), extension of the approach to Antarctic sea ice, incorporation of published methodological improvement, accuracy enhancement in the temporal domain (from year to month to week age information), evaluation and provision of uncertainties, better exploitation of synthetic aperture radar backscatter observations.
7) Sea ice drift (SID): harmonization of SID retrievals across satellite sensors (including synthetic aperture radar), improvement of SID retrieval during summer and in the Antarctic, derivation of retrieval uncertainties, expanding coverage of high-resolution SID data products based on synthetic aperture radar, evaluation of SID CDRs at all scales, improvement of our understanding of uncertainty propagation into deformation parameters.

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