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

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ABSTRACT: Climate observations inform about the past and present state of the climate system. They underpin climate science, guide policies for adaptation and mitigation, and alert populations about 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), that the global community must monitor with the highest standards in the form of Climate Data Records (CDR) are central to GCOS. Today, a single ECV - the sea ice ECV - encapsulates all aspects of the sea-ice environment. It was a single variable in the early 1990s (sea-ice concentration) and 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 adding the new variables under the umbrella of the single sea ice ECV. To start a set of distinct ECVs is indeed critical for not adding to the sub-optimal situation we experience today, and to reconcile the sea ice variables with the practice in other ECV domains. An upcoming opportunity for GCOS to revise its list of ECVs is with its next Implementation Plan in 2022.

CAPSULE: We introduce a set of seven sea ice Essential Climate Variables (ECVs) meant to enter the plans of the Global Climate Observing System (GCOS) from 2022.

1. Introduction

Climate observations underpin climate science and climate services, and inform 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 multi-decadal timescales 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 co-sponsored 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 (IP, in 2004, 2010, 2016) and Progress Reports (in 2009, 2015, 2021). At the time of writing, the current IP 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 characteristics of the CDRs (e.g. in terms of spatial and temporal resolution, accuracy, stability, etc...) to ensure the data records are fit-for-purpose. Funding and implementation agencies external to GCOS use the ECVs and their requirements as targets for their Research and Development (R&D) 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.

GCOS has 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 https://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 multi-variate 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 data-driven inference (Notz and Stroeve 2016). Because of the harshness and remoteness of the polar regions, sea ice CDRs rely mainly upon satellite Earth Observation (EO) data, supported by a limited but indispensable set of in situ observations (buoys, moorings, submarine and ship expeditions and flight campaigns).

Community needs to improve the monitoring of polar regions for mitigation and adaptation measures, together with continued advances in satellite EO technologies and methodologies during the last decade call for a revision of the current single-ECV model that sub-optimally implements the multi-variate sea-ice environment, our main motivation for this contribution. Our paper is structured as follows. In section 2 we introduce the complex sea-ice environment and a set of key variables to describe it. In section 3 we recall how this environment is implemented in the GCOS sea ice ECV today, and what challenges this brings. In section 4, we outline a possible future structure to better serve the sea-ice variables in GCOS. Discussion and outlook are covered in section 5 and we conclude in section 6. 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.

2. The sea ice environment

Sea ice forms from sea water 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. Its melt influences near-surface stratification of the polar and surrounding seas. It extends over between 16 and 28 million square kilometers 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), has become younger (Kwok 2018; Tschudi et al. 2020) and more mobile (Rampal et al. 2009; Kwok et al. 2013; Spreen et al. 2020). This change coincides 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). Alltogether, this has implications for the net radiation balance, heat, momentum and matter fluxes at the ocean-atmosphere interface with consequences for, for example, 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 mid-latitude weather (Cohen et al. 2020). On the one hand, these changes are of advantage 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 land-fast sea ice, results in wave-induced undercutting of permafrost, leading to coastal erosion (Barnhart et al. 2016; Liew et al. 2020) and affects human activities relying on land-fast sea-ice coverage (Cooley et al. 2020). Regional changes in sea-ice cover characteristics affect, e.g., amount and seasonality of primary production (Ardyna and Arrigo 2020; Zhuang et al. 2021) and ocean-atmosphere gas exchange (Lannuzel et al. 2020), prey-predator relationships (Divoky et al. 2021) and fisheries (Huntington et al. 2020; Fauchald et al. 2021).

The sign of changes of the Antarctic sea-ice environment remains uncertain. Its coverage is highly variable (Comiso et al. 2017a; Parkinson 2019) with substantial 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 remains 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 pentade (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 affects 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). Concomitant changes in ice-berg calving and stability of Antarctic land-fast 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 feeds 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 short-wave and long-wave radiation balance. In this context, the sea-ice concentration is essential to know where the surface albedo differs from that of the open ocean. Because the sea-ice albedo varies with 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 vs 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 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 short-wave radiation balance correctly (reflection and transmission) thus requires at least five sea-ice variables. The ice surface temperature is together with the sea-ice concentration the sole parameter determining the up-welling long-wave radiation at the surface, being a key parameter for atmospheric reanalyses (Graham et al. 2019). Its increase concomitant 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 impact on the near-surface air temperature, its horizontal and vertical gradient influences cyclogenesis and -lysis, 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. It is important to monitor this large scale sea-ice mass transport, for example in the Weddell Sea and Ross Sea, and through Fram Strait. This sea-ice mass transport constitutes about one third of the freshwater export out of the Arctic Ocean (Haine et al. 2015) and between 10% and 15% of the total Arctic Ocean sea-ice volume (Spreen et al. 2020). Melting of such volume changes the upper ocean stratification substantially and triggers oceanic processes (Karcher et al. 2005; Haumann et al. 2016). To quantify the freshwater volume transport related to sea ice requires several sea-ice variables including 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). Sea ice density depends on sea-ice age, a proxy for the presence of air bubbles and salt concentration that both drastically change through the first summer melt seasons a sea ice parcel survives to (Vant et al.; Tucker III et al. 1992). Tracking the origin of sea-ice volume requires backward trajectories and thus knowledge of sea-ice drift (Pfirman et al. 1997; Krumpen et al. 2016). Along these trajectories, the sea ice likely changed in response to several local processes: thermodynamic and dynamic thickness

[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).

TABLE 1. Overview of names, short descriptions, main determining processes, and areas of relevance of the core set of seven sea ice variables. Acronyms put in [] in column "determined by" illustrate the links to other sea ice variables.

Sea ice variables			
Name and Acronym	Description	determined by	relevant for
Sea-ice concentration (SIC)	fraction of known ocean area covered by sea ice	ice formation & melt, [SID]	sea-ice area & extent, sea-ice mass
Sea-ice thickness (SIT)	vertical extent of the sea ice	thermodynamic growth & melt, [IST], dynamic processes, [SID]	sea-ice mass ISA, IST, SID
Snow depth (SND)	vertical extent of the snow on top of the sea ice	snow precipitation, accumulation ability, [SIC,SIT,AGE], metamorphism & melt [IST], aeolian redistribution [SIT,AGE]	sea-ice mass ISA, IST
Ice surface albedo (ISA)	ability to reflect solar short wave radiation	[SIT,SND,AGE]	net shortwave surface radiation balance sea-ice mass, area and extent
Ice surface temperature (IST)	ice or snow surface temperature	[SIT,SND,AGE]	net long-wave 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	[SIT,SND,SID]	sea-ice mass ice-type fraction & distribution
Sea ice drift (SID)	lateral movement of the sea ice (transport and deformation)	[SIC,SIT], near-surface wind, ocean surface currents, surface & bottom topography,	SIT distribution, SIC, AGE surface & bottom topography

changes (growth, melt and deformation), and changes to the snow cover (accumulation, melt and metamorphism). Crucial for an adequate quantification of these processes along the trajectory are 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, 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.

3. The GCOS Sea Ice ECV anno 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 (*aka* 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 it is not the case.

A first challenge with the current single-ECV model impacts one of GCOS 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 being an umbrella for widely different geophysical variables, with 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 sub-optimal 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 millions for each ECV (see e.g. Action O35 for sea ice, O36 for ocean colour, 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 and/or requiring very different EO techniques have to spread their "funding unit" across more CDRs. They thus effectively lose traction and make slower progress towards 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 1st "satellite supplement" (GCOS-107, 2006) to the 1st Implementation Plan (GIP, GCOS-92, 2004) that defined only one ECV product for the ECV (O.1 Sea Ice Concentration). Sea-ice 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-154 (2010) to the 2nd Implementation Plan (IP-10, GCOS-138) defined the four ECV products we have today. This was not modified by the 3rd Implementation Plan (GCOS-200, 2016). This summarized history of the sea ice ECV highlights how the new geophysical variables - that were deemed critical and whose observation systems had become mature enough - were added *into* the existing ECV (as additional ECV products) instead of *to the side* (initiating new ECVs). Today’s sub-optimal situation is a direct consequence of this choice.

4. A new structure for the Sea Ice ECV

As seen in section 2, 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.

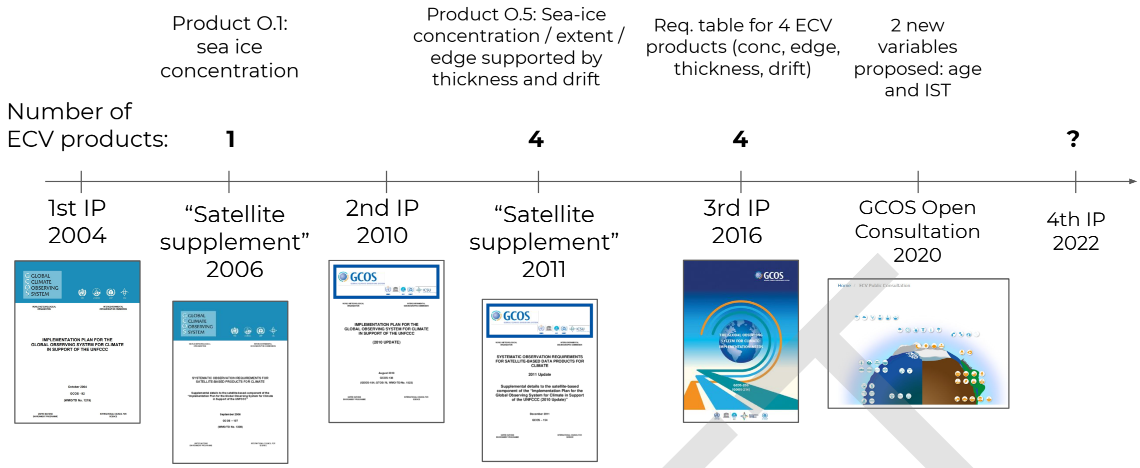

FIG. 1. Evolution of the definition and content of the sea ice ECV, particularly in terms of ECV products, through several GCOS reports.

Owing to technological developments and the dedication of the space agencies and of the research community, the set of EO techniques needed to generate CDRs for the core variables introduced in section 2 is now available (see also Fig. 2).

Sea-ice concentration (SIC) has been derived continuously from satellite microwave brightness temperature (BT) observations since October 1978 for both hemispheres at (mostly) daily temporal resolution. A large set of different algorithms to derive SIC from BT observations exists (Ivanova et al. 2015). SIC CDRs are the backbone of today's knowledge about sea-ice area and extent trends. Several SIC CDRs are supported by operational programs (Lavergne et al. 2019; Peng et al. 2013) and are extended with interim CDRs. Developments towards alternative methodologies and input observations, e.g. optical/infrared or synthetic aperture radar (SAR) 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 (FB) 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 (S. et al. 2003). Alternative SIT data products derived from satellite laser altimeter FB 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 BT 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 surface temperature (IST) 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) CDRs have been derived from satellite BT observations at daily temporal resolution for both hemispheres since 1978 (Markus and Cavalieri 1998; Brucker and Markus 2013). These 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 FB observations is attempted (Guerreiro et al. 2016; Lawrence et al. 2018; Kwok et al. 2020) as is the combination of BT observations with radar altimetry (Xu et al. 2017). These alternative solutions have so far the drawback of a monthly temporal resolution and considerably shorter temporal coverage. At present, a promising avenue is using atmosphere reanalyses informed by in-situ, airborne and satellite observations (Liston et al. 2020; Stroeve et al. 2020). Zhou et al. (2021) presented a first inter-comparison of SND retrieval methods for the Arctic.

Ice surface albedo (ISA) CDRs have 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 BT 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) - also at sub-pixel 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 SIC retrieval from BT observations (Kern et al. 2020).

Sea-ice (and snow) surface temperature (IST) CDRs comprise two flavours. The first kind utilizes satellite infrared temperature (IRT) observations since 1982 at daily (with data gaps) to monthly temporal resolution (Key and Haefliger 1992; Kang et al. 2014; Dybkjær 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; 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 BT 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 insensitive to clouds.

Sea-ice age (AGE) CDRs rely mainly on two EO 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 BT and/or backscatter (BC) observations and classifies the sea-ice cover into age categories[2] (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 vs 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 SIT products (Maslanik et al. 2011; Tschudi et al. 2020; Liu et al. 2020). CDRs of AGE do not yet exist for the Antarctic.

Sea-ice drift (SID) CDRs have been derived in form of large-scale sea-ice motion fields from satellite BT and BC 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;

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

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) triggered further methodological improvements (Kwok 2008; Lavergne et al. 2010). SID data products based on SAR BC exhibit a substantially finer spatial resolution (Kwok et al. 1990; Komarov and Barber 2014; Muckenhuber and Sandven 2017). They have since long 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 coverage with high-resolution SAR BC 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 figure 2 that the core variables require different EO methodologies, although some overlap exists. Different methodologies mean that different expert communities must engage to improve the algorithms and prepare better CDRs. A non-exhaustive list of challenges and required R&D efforts for each variable is compiled in Appendix B.

The seven core sea-ice variables we introduced in section 2 are thus *relevant* (and actually essential), sustained by *feasible* and *cost-effective* observation systems relying heavily on existing satellite EO systems. By filling 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 section 3. 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 nor ECV products.

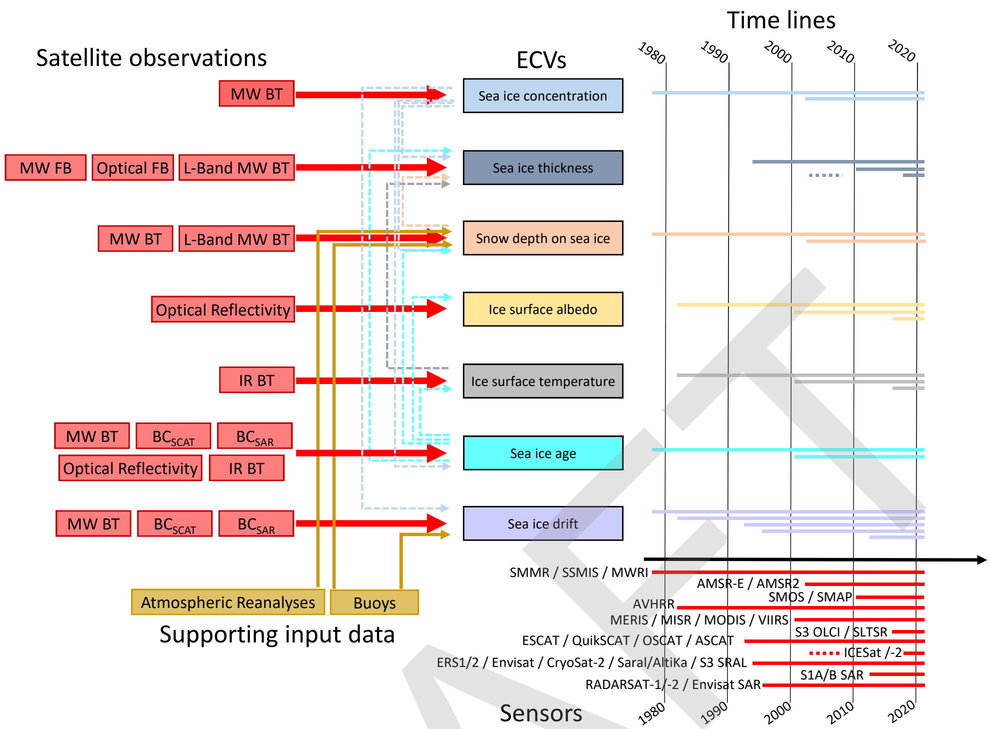

FIG. 2. Overview of the seven ECVs and their potential temporal coverage based on available satellite observations. On the left side we display input satellite observations: MW=microwave, FB=freeboard, BT=brightness temperature, BC=backscatter, IR=infrared, SCAT=scatterometer, SAR=synthetic aperture 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.

5. Discussion and outlook

To introduce seven independent sea-ice related ECVs in GCOS will undoubtedly at first be commented 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 EO technologies. The question is really one of organizing the sea-ice variables to serve GCOS missions at best. 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 section 3, 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 in the other hand (motion: ocean currents vs sea-ice drift, temperature: sea-surface temperature vs ice surface temperature, short-wave radiation: ocean colour vs sea-ice albedo, vertical dimension: sea level vs 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 Photo-synthetic Active Radiation (FAPAR) ECV that has two ECV products, one for modelling (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 EO technologies.

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[3] "Improve quality of snow (ice and sea ice) albedo products" was recently reported as "2 - Started but little progress" by GCOS (2021). It is timely to define the sea-ice albedo ECV as a step towards addressing this action. The same

[3] T stands here for "Terrestrial" since the albedo ECV is only for land surfaces.

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 R&D to improve their reliability, reduce the spread between existing CDRs, and in general progress in maturity towards meeting their specific GCOS requirements. In addition to the specific R&D 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. 2016, updated 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 cover should also continue to be a priority. Transparent inter-comparison 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 fresh water budget of the Arctic including sea-ice mass fluxes towards lower latitudes, 2) the coupling between sea ice, land ice, and fresh water in the Southern Ocean, 3) teleconnections between changes in Arctic sea-ice cover and mid-latitude weather, 4) coastal permafrost erosion and impact on infrastructures and communities, 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 are climate reanalyses, that 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).

6. 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 towards the required monitoring systems, using its Essential Climate Variables (ECV) 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 (section 2). In contrast, a set of four variables is identified by GCOS today as constituents of a single sea ice ECV (GCOS (2016)).

In this contribution (section 3), 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 was also found 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 allow a more complete monitoring of the sea-ice environment and its interactions in the global climate system. These seven variables are essential, feasible, and cost-effective and thus fully qualify as GCOS ECVs.

Furthermore, these seven ECVs do 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 we outlined in section 3, 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 R&D 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). Our 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 the manuscript. To help avoid confusion we also discuss the GCOS terminology and compare it to that used otherwise in the climate community.

a. 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 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.

b. Disambiguation

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

Essential Climate Variables 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, the CDRs are. Various data providers develop different CDRs which target the definition and requirements of an ECV product. There are thus often several CDRs for each ECV product.

B. Research needs for EO monitoring of the seven sea-ice variables

Section 4 presented a list of EO technique 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 R&D efforts to improve the maturity of existing data products and CDRs. We provide here a non exhaustive, non prioritized 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 period, improvement of spatial resolution, ensure long-term inter-sensor consistency.

2. Sea-ice thickness (SIT): hemisphere-specific reduction of retrieval uncertainties (FB, snow depth, densities), move away from using a snow depth climatology, closure of retrieval gap in

summer in the Arctic, extension to early altimeters, ensure consistency across sensors, better exploit SIT proxies such as sea-ice age, address 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, conduct snow depth CDR inter-comparison studies.

4. Ice surface albedo (ISA): ISA CDR evaluation at grid- and sub-grid scale 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 IRT-based IST CDRs, evaluation of BT-based IST CDRs.

6. Sea-ice age (AGE): reconcile the two main approaches (Lagrangian tracking, and age category mapping from BT and BC data), extension of the approach to Antarctic sea ice, incorporation of published methodological improvement, increase the accuracy in the temporal domain (from year to month to week age information), provision of uncertainties and evaluation, better exploitation of SAR BC observations.

7. Sea-ice drift (SID): harmonization of SID retrievals across satellite sensors (including SAR), improvement of SID retrieval during summer and in the Antarctic, derivation of retrieval uncertainties, expanding coverage of high-resolution SAR-based SID data products, evaluation of SID CDRs at all scales, understanding of uncertainty propagation into deformation parameters.

References

Ardhuin, F., M. Otero, S. Merrifield, A. Grouazel, and E. Terrill, 2020: Ice breakup controls dissipation of wind waves across southern ocean sea ice. *Geophysical Research Letters*, **47 (13)**, e2020GL087 699, https://doi.org/10.1029/2020GL087699.

Ardyna, M., and K. R. Arrigo, 2020: Phytoplankton dynamics in a changing arctic ocean. *Nature Climate Change*, **10 (10)**, 892–903, https://doi.org/10.1038/s41558-020-0905-y.

Arrigo, K. R., G. L. van Dijken, and A. L. Strong, 2015: Environmental controls of marine productivity hot spots around antarctica. *Journal of Geophysical Research: Oceans*, **120 (8)**, 5545–5565, https://doi.org/10.1002/2015JC010888.

Atkinson, A., and Coauthors, 2019: Krill (euphausia superba) distribution contracts southward during rapid regional warming. *Nature Climate Change*, **9 (2)**, 142–147, https://doi.org/10.1038/s41558-018-0370-z.

Barnhart, K. R., C. R. Miller, I. Overeem, and J. E. Kay, 2016: Mapping the future expansion of arctic open water. *Nature Climate Change*, **6 (3)**, 280–285, https://doi.org/10.1038/nclimate2848.

Bhatt, U. S., and Coauthors, 2021: Climate drivers of arctic tundra variability and change using an indicators framework. *Environmental Research Letters*, **16 (5)**, 055 019, https://doi.org/10.1088/1748-9326/abe676.

Biggs, T. E. G., S. Alvarez-Fernandez, C. Evans, K. D. A. Mojica, P. D. Rozema, H. J. Venables, D. W. Pond, and C. P. D. Brussaard, 2019: Antarctic phytoplankton community composition and size structure: importance of ice type and temperature as regulatory factors. *Polar Biology*, **42 (11)**, 1997–2015, https://doi.org/10.1007/s00300-019-02576-3.

Bojinski, S., M. Verstraete, T. C. Peterson, C. Richter, A. Simmons, and M. Zemp, 2014: The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, **95 (9)**, 1431 – 1443, https://doi.org/10.1175/BAMS-D-13-00047.1.

Box, J. E., and Coauthors, 2019: Key indicators of arctic climate change: 1971–2017. *Environmental Research Letters*, **14 (4)**, 045 010, https://doi.org/10.1088/1748-9326/aafc1b.

Braakmann-Folgmann, A., and C. Donlon, 2019: Estimating snow depth on arctic sea ice using satellite microwave radiometry and a neural network. *The Cryosphere*, **13 (9)**, 2421–2438, https://doi.org/10.5194/tc-13-2421-2019.

Brean, J., M. Dall'Osto, R. Simó, Z. Shi, D. C. S. Beddows, and R. M. Harrison, 2021: Open ocean and coastal new particle formation from sulfuric acid and amines around the antarctic peninsula. *Nature Geoscience*, **14 (6)**, 383–388, https://doi.org/10.1038/s41561-021-00751-y.

Brodzik, M., D. Long, M. Hardman, A. Paget, and R. Armstrong, 2016, updated 2018: MEaSUREs calibrated enhanced-resolution passive microwave daily EASE-Grid 2.0 brightness temperature ESDR. National Snow and Ice Data Center: Boulder, CO, USA, URL http://nsidc.org/data/nsidc-0630.

Brown, M. S., D. R. Munro, C. J. Feehan, C. Sweeney, H. W. Ducklow, and O. M. Schofield, 2019: Enhanced oceanic co2 uptake along the rapidly changing west antarctic peninsula. *Nature Climate Change*, **9 (9)**, 678–683, https://doi.org/10.1038/s41558-019-0552-3.

Brucker, L., and T. Markus, 2013: Arctic-scale assessment of satellite passive microwave-derived snow depth on sea ice using operation icebridge airborne data. *Journal of Geophysical Research: Oceans*, **118 (6)**, 2892–2905, https://doi.org/10.1002/jgrc.20228.

Cavalieri, D. J., P. Gloersen, and W. J. Campbell, 1984: Determination of sea ice parameters with the NIMBUS 7 SMMR. *Journal of Geophysical Research: Atmospheres*, **89 (D4)**, 5355–5369, https://doi.org/10.1029/JD089iD04p05355.

Cohen, J., and Coauthors, 2020: Divergent consensuses on arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, **10 (1)**, 20–29, https://doi.org/10.1038/s41558-019-0662-y.

Comiso, J., D. Cavalieri, and T. Markus, 2003: Sea ice concentration, ice temperature, and snow depth using AMSR-E data. *IEEE Transactions on Geoscience and Remote Sensing*, **41 (2)**, 243–252, https://doi.org/10.1109/TGRS.2002.808317.

Comiso, J. C., R. A. Gersten, L. V. Stock, J. Turner, G. J. Perez, and K. Cho, 2017a: Positive trend in the antarctic sea ice cover and associated changes in surface temperature. *Journal of Climate*, **30 (6)**, 2251 – 2267, https://doi.org/10.1175/JCLI-D-16-0408.1.

Comiso, J. C., W. N. Meier, and R. Gersten, 2017b: Variability and trends in the arctic sea ice cover: Results from different techniques. *Journal of Geophysical Research: Oceans*, **122 (8)**, 6883–6900, https://doi.org/10.1002/2017JC012768.

Cooley, S. W., J. C. Ryan, L. C. Smith, C. Horvat, B. Pearson, B. Dale, and A. H. Lynch, 2020: Coldest canadian arctic communities face greatest reductions in shorefast sea ice. *Nature Climate Change*, **10 (6)**, 533–538, https://doi.org/10.1038/s41558-020-0757-5.

David, C. L., and Coauthors, 2021: Sea-ice habitat minimizes grazing impact and predation risk for larval antarctic krill. *Polar Biology*, **44 (6)**, 1175–1193, https://doi.org/10.1007/s00300-021-02868-7.

Davy, R., and S. Outten, 2020: The arctic surface climate in cmip6: Status and developments since cmip5. *Journal of Climate*, **33 (18)**, 8047 – 8068, https://doi.org/10.1175/JCLI-D-19-0990.1.

Divoky, G. J., E. Brown, and K. H. Elliott, 2021: Reduced seasonal sea ice and increased sea surface temperature change prey and foraging behaviour in an ice-obligate arctic seabird, mandt's black guillemot (cepphus grylle mandtii). *Polar Biology*, **44 (4)**, 701–715, https://doi.org/10.1007/s00300-021-02826-3.

Dodd, E. M. A., K. L. Veal, D. J. Ghent, M. R. van den Broeke, and J. J. Remedios, 2019: Toward a combined surface temperature data set for the arctic from the along-track scanning radiometers. *Journal of Geophysical Research: Atmospheres*, **124**, 6718–6736, https://doi.org/10.1029/2019JD030262.

Drucker, R., S. Martin, and R. Kwok, 2011: Sea ice production and export from coastal polynyas in the weddell and ross seas. *Geophysical Research Letters*, **38 (17)**, https://doi.org/10.1029/2011GL048668.

Dybkjær, G., S. Eastwood, A. L. Borg, J. L. Høyer, and R. Tonboe, 2018: Osi saf algorithm theoretical basis document for the osi saf high latitude l2 sea and sea ice surface temperature l2 processing chain. osi-205-a and osi-205-b. EUMETSAT, URL https://osisaf-hl.met.no/sites/osisaf-hl.met.no/files/baseline_document/osisaf_cdop3_ss2_atbd_hl-l2-sst-ist_v1p4.pdf.

Fan, P., X. Pang, X. Zhao, M. Shokr, R. Lei, M. Qu, Q. Ji, and M. Ding, 2020: Sea ice surface temperature retrieval from Landsat 8/TIRS: Evaluation of five methods against in situ temperature records and MODIS IST in arctic region. *Remote Sensing of Environment*, **248**, 111 975, https://doi.org/10.1016/j.rse.2020.111975.

Fauchald, P., P. Arneberg, J. B. Debernard, S. Lind, E. Olsen, and V. H. Hausner, 2021: Poleward shifts in marine fisheries under arctic warming. *Environmental Research Letters*, **16 (7)**, 074 057, https://doi.org/10.1088/1748-9326/ac1010.

Fennig, K., M. Schröder, A. Andersson, and R. Hollmann, 2020: A fundamental climate data record of smmr, ssm/i, and ssmis brightness temperatures. *Earth System Science Data*, **12 (1)**, 647–681, https://doi.org/10.5194/essd-12-647-2020.

Fraser, A. D., and Coauthors, 2019: Landfast ice controls on sea-ice production in the cape darnley polynya: A case study. *Remote Sensing of Environment*, **233**, 111 315, https://doi.org/10.1016/j.rse.2019.111315.

GCOS, 2016: GCOS-200. The global observing system for climate: Implementation needs. World Meteorological Organization, URL https://gcos.wmo.int/en/gcos-implementation-plan.

GCOS, 2021: GCOS-240. The status of the global climate observing system 2021: The gcos status report. World Meteorological Organization, URL https://gcos.wmo.int/en/gcos-status-report-2021.

Girard-Ardhuin, F., and R. Ezraty, 2012: Enhanced arctic sea ice drift estimation merging radiometer and scatterometer data. *IEEE Transactions on Geoscience and Remote Sensing*, **50 (7)**, 2639–2648, https://doi.org/10.1109/TGRS.2012.2184124.

Graham, R. M., and Coauthors, 2019: Evaluation of six atmospheric reanalyses over arctic sea ice from winter to early summer. *Journal of Climate*, **32 (14)**, 4121 – 414, https://doi.org/10.1175/JCLI-D-18-0643.1.

Guerreiro, K., S. Fleury, E. Zakharova, F. Rémy, and A. Kouraev, 2016: Potential for estimation of snow depth on arctic sea ice from CryoSat-2 and SARAL/AltiKa missions. *Remote Sensing of Environment*, **186**, 339–349, https://doi.org/10.1016/j.rse.2016.07.013.

Haine, T. W., and Coauthors, 2015: Arctic freshwater export: Status, mechanisms, and prospects. *Global and Planetary Change*, **125**, 13–35, https://doi.org/10.1016/j.gloplacha.2014.11.013.

Haumann, F. A., N. Gruber, M. Münnich, I. Frenger, and S. Kern, 2016: Sea-ice transport driving southern ocean salinity and its recent trends. *Nature*, **537 (7618)**, 89–92, https://doi.org/10.1038/nature19101.

Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146 (730)**, 1999–2049, https://doi.org/10.1002/qj.3803.

Hobbs, W. R., R. Massom, S. Stammerjohn, P. Reid, G. Williams, and W. Meier, 2016: A review of recent changes in southern ocean sea ice, their drivers and forcings. *Global and Planetary Change*, **143**, 228–250, https://doi.org/10.1016/j.gloplacha.2016.06.008.

Høyer, J. L., G. Dybkjær, S. Eastwood, and K. S. Madsen, 2019: Eustace/aasti: Global clear-sky ice surface temperature data from the avhrr series on the satellite swath with estimates of uncertainty components, v1.1, 2000-2009. Centre for Environmental Data Analysis, https://doi.org/10.5285/60b820fa10804fca9c3f1ddfa5ef42a1.

Høyer, J. L., A. Lang, R. Tonboe, S. Eastwood, W. Wimmer, and G. Dybkjær, 2017: Report from field inter comparison experiment (fice) for ice surface temperature. ESA, URL http://www.frm4sts.org/wp-content/uploads/sites/3/2017/12/OFE-OP-40-TR-5-V1-Iss-1-Ver-1-Signed.pdf.

Hückstädt, L. A., and Coauthors, 2020: Projected shifts in the foraging habitat of crabeater seals along the antarctic peninsula. *Nature Climate Change*, **10 (5)**, 472–477, https://doi.org/10.1038/s41558-020-0745-9.

Huntington, H. P., and Coauthors, 2020: Evidence suggests potential transformation of the pacific arctic ecosystem is underway. *Nature Climate Change*, **10 (4)**, 342–348, https://doi.org/10.1038/s41558-020-0695-2.

Hutter, N., L. Zampieri, and M. Losch, 2019: Leads and ridges in arctic sea ice from rgps data and a new tracking algorithm. *The Cryosphere*, **13 (2)**, 627–645, https://doi.org/10.5194/tc-13-627-2019.

Istomina, L., H. Marks, M. Huntemann, G. Heygster, and G. Spreen, 2020: Improved cloud detection over sea ice and snow during arctic summer using meris data. *Atmospheric Measurement Techniques*, **13 (12)**, 6459–6472, https://doi.org/10.5194/amt-13-6459-2020.

Ivanova, N., and Coauthors, 2015: Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations. *The Cryosphere*, **9 (5)**, 1797–1817, https://doi.org/10.5194/tc-9-1797-2015.

Jena, B., and A. N. Pillai, 2020: Satellite observations of unprecedented phytoplankton blooms in the maud rise polynya, southern ocean. *The Cryosphere*, **14 (4)**, 1385–1398, https://doi.org/10.5194/tc-14-1385-2020.

Kacimi, S., and R. Kwok, 2020: The antarctic sea ice cover from icesat-2 and cryosat-2: freeboard, snow depth, and ice thickness. *The Cryosphere*, **14 (12)**, 4453–4474, https://doi.org/10.5194/tc-14-4453-2020.

Kang, D., J. Im, M.-I. Lee, and L. J. Quackenbush, 2014: The MODIS ice surface temperature product as an indicator of sea ice minimum over the arctic ocean. *Remote Sensing of Environment*, **152**, 99–108, https://doi.org/10.1016/j.rse.2014.05.012.

Karcher, M., R. Gerdes, F. Kauker, C. Köberle, and I. Yashayaev, 2005: Arctic ocean change heralds north atlantic freshening. *Geophysical Research Letters*, **32 (21)**, https://doi.org/10.1029/2005GL023861.

Karlsson, K.-G., and Coauthors, 2017: CLARA-A2: the second edition of the CM SAF cloud and radiation data record from 34 years of global AVHRR data. *Atmospheric Chemistry and Physics*, **17 (9)**, 5809–5828, https://doi.org/10.5194/acp-17-5809-2017.

Katlein, C., and Coauthors, 2015: Influence of ice thickness and surface properties on light transmission through arctic sea ice. *Journal of Geophysical Research: Oceans*, **120 (9)**, 5932–5944, https://doi.org/10.1002/2015JC010914.

Kern, S., T. Lavergne, D. Notz, L. T. Pedersen, and R. Tonboe, 2020: Satellite passive microwave sea-ice concentration data set inter-comparison for arctic summer conditions. *The Cryosphere*, **14 (7)**, 2469–2493, https://doi.org/10.5194/tc-14-2469-2020.

Kern, S., T. Lavergne, D. Notz, L. T. Pedersen, R. T. Tonboe, R. Saldo, and A. M. Sørensen, 2019: Satellite passive microwave sea-ice concentration data set intercomparison: closed ice and ship-based observations. *The Cryosphere*, **13 (12)**, 3261–3307, https://doi.org/10.5194/tc-13-3261-2019.

Kern, S., and B. Ozsoy, 2019: An attempt to improve snow depth retrieval using satellite microwave radiometry for rough antarctic sea ice. *Remote Sensing*, **11 (19)**, 2323–2353, https://doi.org/10.3390/rs11192323.

Kern, S., B. Ozsoy-Çiçek, and A. Worby, 2016: Antarctic sea-ice thickness retrieval from ICESat: Inter-comparison of different approaches. *Remote Sensing*, **8 (7)**, 538–564, https://doi.org/10.3390/rs8070538.

Key, J., and M. Haefliger, 1992: Arctic ice surface temperature retrieval from AVHRR thermal channels. *Journal of Geophysical Research: Atmospheres*, **97 (D5)**, 5885–5893, https://doi.org/https://doi.org/10.1029/92JD00348.

Key, J., X. Wang, Y. Liu, R. Dworak, and A. Letterly, 2016: The AVHRR polar pathfinder climate data records. *Remote Sensing*, **8 (3)**, 167–185, https://doi.org/10.3390/rs8030167.

Kharbouche, S., and J.-P. Muller, 2018: Sea ice albedo from MISR and MODIS: Production, validation, and trend analysis. *Remote Sensing*, **11 (1)**, 9–26, https://doi.org/10.3390/rs11010009.

Kilic, L., R. T. Tonboe, C. Prigent, and G. Heygster, 2019: Estimating the snow depth, the snow–ice interface temperature, and the effective temperature of arctic sea ice using advanced microwave scanning radiometer 2 and ice mass balance buoy data. *The Cryosphere*, **13 (4)**, 1283–1296, https://doi.org/10.5194/tc-13-1283-2019.

Kitade, Y., and Coauthors, 2014: Antarctic bottom water production from the vincennes bay polynya, east antarctica. *Geophysical Research Letters*, **41 (10)**, 3528–3534, https://doi.org/10.1002/2014GL059971.

Komarov, A. S., and D. G. Barber, 2014: Sea ice motion tracking from sequential dual-polarization RADARSAT-2 images. *IEEE Transactions on Geoscience and Remote Sensing*, **52 (1)**, 121–136, https://doi.org/10.1109/TGRS.2012.2236845.

Komarov, A. S., and M. Buehner, 2021: Ice concentration from dual-polarization SAR images using ice and water retrievals at multiple spatial scales. *IEEE Transactions on Geoscience and Remote Sensing*, **59 (2)**, 950–961, https://doi.org/10.1109/TGRS.2020.3000672.

Korosov, A. A., and Coauthors, 2018: A new tracking algorithm for sea ice age distribution estimation. *The Cryosphere*, **12 (6)**, 2073–2085, https://doi.org/10.5194/tc-12-2073-2018.

Krumpen, T., R. Gerdes, C. Haas, S. Hendricks, A. Herber, V. Selyuzhenok, L. Smedsrud, and G. Spreen, 2016: Recent summer sea ice thickness surveys in fram strait and associated ice volume fluxes. *The Cryosphere*, **10 (2)**, 523–534, https://doi.org/10.5194/tc-10-523-2016.

Kurtz, N. T., and T. Markus, 2012: Satellite observations of antarctic sea ice thickness and volume. *Journal of Geophysical Research: Oceans*, **117 (C8)**, https://doi.org/10.1029/2012JC008141.

Kusahara, K., G. D. Williams, T. Tamura, R. Massom, and H. Hasumi, 2017: Dense shelf water spreading from antarctic coastal polynyas to the deep southern ocean: A regional circumpolar model study. *Journal of Geophysical Research: Oceans*, **122 (8)**, 6238–6253, https://doi.org/10.1002/2017JC012911.

Kwok, R., 2008: Summer sea ice motion from the 18 ghz channel of AMSR-E and the exchange of sea ice between the pacific and atlantic sectors. *Geophysical Research Letters*, **35 (3)**, https://doi.org/10.1029/2007GL032692.

Kwok, R., 2018: Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958-2018). *Environmental Research Letters*, **13 (10)**, 105 005, https://doi.org/10.1088/1748-9326/aae3ec.

Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi, 2009: Thinning and volume loss of the arctic ocean sea ice cover: 2003–2008. *Journal of Geophysical Research: Oceans*, **114 (C7)**, https://doi.org/10.1029/2009JC005312.

Kwok, R., J. Curlander, R. McConnell, and S. Pang, 1990: An ice-motion tracking system at the Alaska SAR facility. *IEEE Journal of Oceanic Engineering*, **15 (1)**, 44–54, https://doi.org/10.1109/48.46835.

Kwok, R., S. Kacimi, M. Webster, N. Kurtz, and A. Petty, 2020: Arctic snow depth and sea ice thickness from ICESat-2 and CryoSat-2 freeboards: A first examination. *Journal of Geophysical Research: Oceans*, **125 (3)**, https://doi.org/10.1029/2019JC016008.

Kwok, R., A. A. Petty, M. Bagnardi, N. T. Kurtz, G. F. Cunningham, A. Ivanoff, and S. Kacimi, 2021: Refining the sea surface identification approach for determining freeboards in the icesat-2 sea ice products. *The Cryosphere*, **15 (2)**, 821–833, https://doi.org/10.5194/tc-15-821-2021.

Kwok, R., D. A. Rothrock, H. L. Stern, and G. F. Cunningham, 1995: Determination of the age distribution of sea ice from lagrangian observations of ice motion. *IEEE Transactions on Geoscience and Remote Sensing*, **33 (2)**, 392–400, https://doi.org/10.1109/TGRS.1995.8746020.

Kwok, R., A. Schweiger, D. A. Rothrock, S. Pang, and C. Kottmeier, 1998: Sea ice motion from satellite passive microwave imagery assessed with ERS SAR and buoy motions. *Journal of Geophysical Research: Oceans*, **103 (C4)**, 8191–8214, https://doi.org/10.1029/97JC03334.

Kwok, R., G. Spreen, and S. Pang, 2013: Arctic sea ice circulation and drift speed: Decadal trends and ocean currents. *Journal of Geophysical Research: Oceans*, **118 (5)**, 2408–2425, https://doi.org/10.1002/jgrc.20191.

Laine, V., T. Manninen, and A. Riihelä, 2014: High temporal resolution estimations of the arctic sea ice albedo during the melting and refreezing periods of the years 2003-2011. *Remote Sensing of Environment*, **140**, 604–613, https://doi.org/10.1016/j.rse.2013.10.001.

Lannuzel, D., and Coauthors, 2020: The future of arctic sea-ice biogeochemistry and ice-associated ecosystems. *Nature Climate Change*, **10 (11)**, 983–992, https://doi.org/10.1038/s41558-020-00940-4.

Lavergne, T., S. Eastwood, Z. Teffah, H. Schyberg, and L.-A. Breivik, 2010: Sea ice motion from low-resolution satellite sensors: An alternative method and its validation in the arctic. *Journal of Geophysical Research: Oceans*, **115 (C10)**, https://doi.org/10.1029/2009JC005958.

Lavergne, T., and Coauthors, 2019: Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records. *The Cryosphere*, **13 (1)**, 49–78, https://doi.org/10.5194/tc-13-49-2019.

Lawrence, I. R., M. C. Tsamados, J. C. Stroeve, T. W. K. Armitage, and A. L. Ridout, 2018: Estimating snow depth over arctic sea ice from calibrated dual-frequency radar freeboards. *The Cryosphere*, **12 (11)**, 3551–3564, https://doi.org/10.5194/tc-12-3551-2018.

Lee, S., J. Stroeve, M. Tsamados, and A. L. Khan, 2020: Machine learning approaches to retrieve pan-arctic melt ponds from visible satellite imagery. *Remote Sensing of Environment*, **247**, 111 919, https://doi.org/10.1016/j.rse.2020.111919.

Lee, S.-M., and B.-J. Sohn, 2015: Retrieving the refractive index, emissivity, and surface temperature of polar sea ice from 6.9ghz microwave measurements: A theoretical development. *Journal of Geophysical Research: Atmospheres*, **120 (6)**, 2293–2305, https://doi.org/10.1002/2014JD022481.

Lee, S.-M., B.-J. Sohn, and S.-J. Kim, 2017: Differentiating between first-year and multiyear sea ice in the arctic using microwave-retrieved ice emissivities. *Journal of Geophysical Research: Atmospheres*, **122 (10)**, 5097–5112, https://doi.org/10.1002/2016JD026275.

Lee, S.-M., B.-J. Sohn, and C. Kummerow, 2018: Long-term arctic snow/ice interface temperature from special sensor for microwave imager measurements. *Remote Sensing*, **10 (11)**, 1795–1809, https://doi.org/10.3390/rs10111795.

Lellouche, J.-M., and Coauthors, 2021: The copernicus global 1/12° oceanic and sea ice GLORYS12 reanalysis. *Frontiers in Earth Science*, **9**, 585, https://doi.org/10.3389/feart.2021.698876.

Li, H., H. Xie, S. Kern, W. Wan, B. Ozsoy, S. Ackley, and Y. Hong, 2018: Spatio-temporal variability of antarctic sea-ice thickness and volume obtained from icesat data using an innovative algorithm. *Remote Sensing of Environment*, **219**, 44–61, https://doi.org/10.1016/j.rse.2018.09.031.

Li, X., N. Otsuka, and L. W. Brigham, 2021: Spatial and temporal variations of recent shipping along the northern sea route. *Polar Science*, **27**, 100 569, https://doi.org/10.1016/j.polar.2020.100569, arctic Challenge for Sustainability Project (ArCS).

Liew, M., M. Xiao, B. M. Jones, L. M. Farquharson, and V. E. Romanovsky, 2020: Prevention and control measures for coastal erosion in northern high-latitude communities: a systematic review based on alaskan case studies. *Environmental Research Letters*, **15 (9)**, 093 002, https://doi.org/10.1088/1748-9326/ab9387.

Lindell, D., and D. Long, 2016: Multiyear arctic ice classification using ASCAT and SSMIS. *Remote Sensing*, **8 (4)**, 294–312, https://doi.org/10.3390/rs8040294.

Lindstrom, E., J. Gunn, A. Fischer, A. McCurdy, L. Glover, and the Task Team for an Integrated Framework for Sustained Ocean Observing, 2012: IOC/INF-1284. A framework for ocean observing. UNESCO, URL https://www.eoos-ocean.eu/download/GOOSFrameworkOceanObserving.pdf, https://doi.org/10.5270/OceanObs09-FOO.

Liston, G. E., P. Itkin, J. Stroeve, M. Tschudi, J. S. Stewart, S. H. Pedersen, A. K. Reinking, and K. Elder, 2020: A lagrangian snow-evolution system for sea-ice applications (snowmodel-lg):

Part i—model description. *Journal of Geophysical Research: Oceans*, **125 (10)**, https://doi.org/10.1029/2019JC015913.

Liu, Y., R. Dworak, and J. Key, 2018: Ice surface temperature retrieval from a single satellite imager band. *Remote Sensing*, **10 (12)**, 1909–1920, https://doi.org/10.3390/rs10121909.

Liu, Y., J. R. Key, X. Wang, and M. Tschudi, 2020: Multidecadal arctic sea ice thickness and volume derived from ice age. *The Cryosphere*, **14 (4)**, 1325–1345, https://doi.org/10.5194/tc-14-1325-2020.

Ludwig, V., G. Spreen, and L. T. Pedersen, 2020: Evaluation of a new merged sea-ice concentration dataset at 1 km resolution from thermal infrared and passive microwave satellite data in the arctic. *Remote Sensing*, **12 (19)**, 3183, https://doi.org/10.3390/rs12193183.

Maaß, N., L. Kaleschke, X. Tian-Kunze, and M. Drusch, 2013: Snow thickness retrieval over thick arctic sea ice using smos satellite data. *The Cryosphere*, **7 (6)**, 1971–1989, https://doi.org/10.5194/tc-7-1971-2013.

Mäkynen, M., and J. Karvonen, 2017: MODIS sea ice thickness and open water–sea ice charts over the barents and kara seas for development and validation of sea ice products from microwave sensor data. *Remote Sensing*, **9 (12)**, 1324–1361, https://doi.org/10.3390/rs9121324.

Markus, T., and D. J. Cavalieri, 1998: *Snow Depth Distribution Over Sea Ice in the Southern Ocean from Satellite Passive Microwave Data*, 19–39. American Geophysical Union (AGU), https://doi.org/10.1029/AR074p0019.

Markus, T., R. Massom, A. Worby, V. Lytle, N. Kurtz, and T. Maksym, 2011: Freeboard, snow depth and sea-ice roughness in east antarctica from in situ and multiple satellite data. *Annals of Glaciology*, **52 (57)**, 242–248, https://doi.org/10.3189/172756411795931570.

Maslanik, J., J. Stroeve, C. Fowler, and W. Emery, 2011: Distribution and trends in arctic sea ice age through spring 2011. *Geophysical Research Letters*, **38 (13)**, https://doi.org/10.1029/2011GL047735.

Massom, R. A., A. B. Giles, H. A. Fricker, R. C. Warner, B. Legrésy, G. Hyland, N. Young, and A. D. Fraser, 2010: Examining the interaction between multi-year landfast sea ice and the mertz glacier tongue, east antarctica: Another factor in ice sheet stability? *Journal of Geophysical Research: Oceans*, **115 (C12)**, https://doi.org/10.1029/2009JC006083.

Massom, R. A., A. B. Giles, R. C. Warner, H. A. Fricker, B. Legrésy, G. Hyland, L. Lescarmontier, and N. Young, 2015: External influences on the mertz glacier tongue (east antarctica) in the decade leading up to its calving in 2010. *Journal of Geophysical Research: Earth Surface*, **120 (3)**, 490–506, https://doi.org/10.1002/2014JF003223.

Melia, N., K. Haines, and E. Hawkins, 2016: Sea ice decline and 21st century trans-arctic shipping routes. *Geophysical Research Letters*, **43 (18)**, 9720–9728, https://doi.org/10.1002/2016GL069315.

Muckenhuber, S., and S. Sandven, 2017: Open-source sea ice drift algorithm for sentinel-1 sar imagery using a combination of feature tracking and pattern matching. *The Cryosphere*, **11 (4)**, 1835–1850, https://doi.org/10.5194/tc-11-1835-2017.

Mudryk, L. R., J. Dawson, S. E. L. Howell, C. Derksen, T. A. Zagon, and M. Brady, 2021: *Nature Climate Change*, **11 (8)**, 673–679, https://doi.org/10.1038/s41558-021-01087-6.

Nicolaus, M., S. Gerland, S. R. Hudson, S. Hanson, J. Haapala, and D. K. Perovich, 2010: Seasonality of spectral albedo and transmittance as observed in the arctic transpolar drift in 2007. *Journal of Geophysical Research: Oceans*, **115 (C11)**, https://doi.org/10.1029/2009JC006074.

Nihashi, S., and K. I. Ohshima, 2015: Circumpolar mapping of antarctic coastal polynyas and landfast sea ice: Relationship and variability. *Journal of Climate*, **28 (9)**, 3650 – 3670, https://doi.org/10.1175/JCLI-D-14-00369.1.

Notz, D., and SIMIP Community, 2020: Arctic sea ice in CMIP6. *Geophysical Research Letters*, **47 (10)**, https://doi.org/10.1029/2019GL086749.

Notz, D., and J. Stroeve, 2016: Observed arctic sea-ice loss directly follows anthropogenic co₂ emission. *Science*, **354 (6313)**, 747–750, https://doi.org/10.1126/science.aag2345.

Ohshima, K. I., and Coauthors, 2013: Antarctic bottom water production by intense sea-ice formation in the cape darnley polynya. *Nature Geoscience*, **6 (3)**, 235–240, https://doi.org/10.1038/ngeo1738.

Parkinson, C. L., 2019: A 40-y record reveals gradual antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the arctic. *Proceedings of the National Academy of Sciences*, **116 (29)**, 14 414–14 423, https://doi.org/10.1073/pnas.1906556116.

Parkinson, C. L., and N. E. DiGirolamo, 2021: Sea ice extents continue to set new records: Arctic, antarctic, and global results. *Remote Sensing of Environment*, **267**, 112 753, https://doi.org/10.1016/j.rse.2021.112753.

Paul, S., S. Hendricks, R. Ricker, S. Kern, and E. Rinne, 2018: Empirical parametrization of envisat freeboard retrieval of arctic and antarctic sea ice based on cryosat-2: progress in the esa climate change initiative. *The Cryosphere*, **12 (7)**, 2437–2460, https://doi.org/10.5194/tc-12-2437-2018.

Peng, G., W. N. Meier, D. J. Scott, and M. H. Savoie, 2013: A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring. *Earth System Science Data*, **5 (2)**, 311–318, https://doi.org/10.5194/essd-5-311-2013.

Peng, J., Y. Yu, P. Yu, and S. Liang, 2018: The VIIRS sea-ice albedo product generation and preliminary validation. *Remote Sensing*, **10 (11)**, 1826–1848, https://doi.org/10.3390/rs10111826.

Perovich, D. K., 1996: The optical properties of sea ice. U.S. Cold Reg. Res. and Eng. Lab., 25 pp.

Perovich, D. K., B. Light, H. Eicken, K. F. Jones, K. Runciman, and S. V. Nghiem, 2007: Increasing solar heating of the arctic ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback. *Geophysical Research Letters*, **34 (19)**, https://doi.org/10.1029/2007GL031480.

Pfirman, S. L., R. Colony, D. Nürnberg, H. Eicken, and I. Rigor, 1997: Reconstructing the origin and trajectory of drifting arctic sea ice. *Journal of Geophysical Research: Oceans*, **102 (C6)**, 12 575–12 586, https://doi.org/10.1029/96JC03980.

Pohl, C., L. Istomina, S. Tietsche, E. Jäkel, J. Stapf, G. Spreen, and G. Heygster, 2020: Broadband albedo of arctic sea ice from meris optical data. *The Cryosphere*, **14 (1)**, 165–182, https://doi.org/10.5194/tc-14-165-2020.

Rampal, P., V. Dansereau, E. Olason, S. Bouillon, T. Williams, A. Korosov, and A. Samaké, 2019: On the multi-fractal scaling properties of sea ice deformation. *The Cryosphere*, **13 (9)**, 2457–2474, https://doi.org/10.5194/tc-13-2457-2019.

Rampal, P., J. Weiss, and D. Marsan, 2009: Positive trend in the mean speed and deformation rate of arctic sea ice, 1979–2007. *Journal of Geophysical Research: Oceans*, **114 (C5)**, https://doi.org/10.1029/2008JC005066.

Ricker, R., S. Hendricks, L. Kaleschke, X. Tian-Kunze, J. King, and C. Haas, 2017: A weekly arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data. *The Cryosphere*, **11 (4)**, 1607–1623, https://doi.org/10.5194/tc-11-1607-2017.

Roach, L. A., and Coauthors, 2020: Antarctic sea ice area in cmip6. *Geophysical Research Letters*, **47 (9)**, https://doi.org/10.1029/2019GL086729.

Rösel, A., and L. Kaleschke, 2012: Exceptional melt pond occurrence in the years 2007 and 2011 on the arctic sea ice revealed from modis satellite data. *Journal of Geophysical Research: Oceans*, **117 (C5)**, https://doi.org/10.1029/2011JC007869.

Rostosky, P., G. Spreen, S. L. Farrell, T. Frost, G. Heygster, and C. Melsheimer, 2018: Snow depth retrieval on arctic sea ice from passive microwave radiometers-improvements and extensions to multiyear ice using lower frequencies. *Journal of Geophysical Research: Oceans*, **123 (10)**, 7120–7138, https://doi.org/10.1029/2018JC014028.

S., L., P. N., and S. D., 2003: High interannual variability of sea ice thickness in the arctic region. *Nature*, **425**, 947–950, https://doi.org/10.1038/nature02050.

Sallila, H., S. L. Farrell, J. McCurry, and E. Rinne, 2019: Assessment of contemporary satellite sea ice thickness products for arctic sea ice. *The Cryosphere*, **13 (4)**, 1187–1213, https://doi.org/10.5194/tc-13-1187-2019.

Schultz, C., S. C. Doney, J. Hauck, M. T. Kavanaugh, and O. Schofield, 2021: Modeling phytoplankton blooms and inorganic carbon responses to sea-ice variability in the west antarctic peninsula. *Journal of Geophysical Research: Biogeosciences*, **126 (4)**, https://doi.org/10.1029/2020JG006227.

Schwegmann, S., C. Haas, C. Fowler, and R. Gerdes, 2011: A comparison of satellite-derived sea-ice motion with drifting-buoy data in the weddell sea, antarctica. *Annals of Glaciology*, **52 (57)**, 103–110, https://doi.org/10.3189/172756411795931813.

Shepherd, A., H. A. Fricker, and S. L. Farrell, 2018: Trends and connections across the antarctic cryosphere. *Nature*, **558 (7709)**, 223–232, https://doi.org/10.1038/s41586-018-0171-6.

Spreen, G., L. de Steur, D. Divine, S. Gerland, E. Hansen, and R. Kwok, 2020: Arctic sea ice volume export through fram strait from 1992 to 2014. *Journal of Geophysical Research: Oceans*, **125 (6)**, https://doi.org/10.1029/2019JC016039.

Stroeve, J., and D. Notz, 2018: Changing state of arctic sea ice across all seasons. *Environmental Research Letters*, **13 (10)**, 103 001, https://doi.org/10.1088/1748-9326/aade56, URL https://doi.org/10.1088/1748-9326/aade56.

Stroeve, J., and Coauthors, 2020: A lagrangian snow evolution system for sea ice applications (snowmodel-lg): Part ii—analyses. *Journal of Geophysical Research: Oceans*, **125 (10)**, https://doi.org/10.1029/2019JC015900.

Stroeve, J. C., S. Jenouvrier, G. G. Campbell, C. Barbraud, and K. Delord, 2016: Mapping and assessing variability in the antarctic marginal ice zone, pack ice and coastal polynyas in two sea ice algorithms with implications on breeding success of snow petrels. *The Cryosphere*, **10 (4)**, 1823–1843, https://doi.org/10.5194/tc-10-1823-2016.

Stroeve, J. C., T. Markus, L. Boisvert, J. Miller, and A. Barrett, 2014: Changes in arctic melt season and implications for sea ice loss. *Geophysical Research Letters*, **41 (4)**, 1216–1225, https://doi.org/10.1002/2013GL058951.

Sumata, H., R. Kwok, R. Gerdes, F. Kauker, and M. Karcher, 2015: Uncertainty of arctic summer ice drift assessed by high-resolution sar data. *Journal of Geophysical Research: Oceans*, **120 (8)**, 5285–5301, https://doi.org/10.1002/2015JC010810.

Sumata, H., T. Lavergne, F. Girard-Ardhuin, N. Kimura, M. A. Tschudi, F. Kauker, M. Karcher, and R. Gerdes, 2014: An intercomparison of arctic ice drift products to deduce uncertainty estimates. *Journal of Geophysical Research: Oceans*, **119 (8)**, 4887–4921, https://doi.org/10.1002/2013JC009724.

Swan, A. M., and D. G. Long, 2012: Multiyear arctic sea ice classification using QuikSCAT. *IEEE Transactions on Geoscience and Remote Sensing*, **50 (9)**, 3317–3326, https://doi.org/10.1109/TGRS.2012.2184123.

Tamura, T., K. I. Ohshima, A. D. Fraser, and G. D. Williams, 2016: Sea ice production variability in antarctic coastal polynyas. *Journal of Geophysical Research: Oceans*, **121 (5)**, 2967–2979, https://doi.org/.1002/2015JC011537.

Theocharous, E., and N. Fox, ????: Fiducial reference measurements for validation of surface temperature from satellites (frm4sts) - laboratory calibration of participants radiometers and blackbodies. protocol for the frm4sts lce (lce-ip). ESA.

Tian-Kunze, X., L. Kaleschke, N. Maaß, M. Mäkynen, N. Serra, M. Drusch, and T. Krumpen, 2014: SMOS-derived thin sea ice thickness: algorithm baseline, product specifications and initial verification. *The Cryosphere*, **8 (3)**, 997–1018, https://doi.org/10.5194/tc-8-997-2014.

Tilling, R., A. Ridout, and A. Shepherd, 2019: Assessing the impact of lead and floe sampling on arctic sea ice thickness estimates from envisat and cryosat-2. *Journal of Geophysical Research: Oceans*, **124 (11)**, 7473–7485, https://doi.org/10.1029/2019JC015232.

Timmermans, M.-L., and J. Marshall, 2020: Understanding arctic ocean circulation: A review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, **125 (4)**, https://doi.org/10.1029/2018JC014378.

Trewin, B., A. Cazenave, S. Howell, M. Huss, K. Isensee, M. D. Palmer, O. Tarasova, and A. Vermeulen, 2021: Headline indicators for global climate monitoring. *Bulletin of the American Meteorological Society*, **102 (1)**, E20 – E37, https://doi.org/10.1175/BAMS-D-19-0196.1.

Tschudi, M. A., W. N. Meier, and J. S. Stewart, 2020: An enhancement to sea ice motion and age products at the national snow and ice data center (NSIDC). *The Cryosphere*, **14 (5)**, 1519–1536, https://doi.org/10.5194/tc-14-1519-2020.

Tucker III, W. B., D. K. Perovich, A. J. Gow, W. F. Weeks, and M. R. Drinkwater, 1992: *Physical Properties of Sea Ice Relevant to Remote Sensing*, chap. 2, 9–28. American Geophysical Union (AGU), https://doi.org/10.1029/GM068p0009.

Turner, J., and Coauthors, 2020: Recent decrease of summer sea ice in the weddell sea, antarctica. *Geophysical Research Letters*, **47 (11)**, e2020GL087 127, https://doi.org/10.1029/2020GL087127.

Vant, M. R., R. B. Gray, R. O. Ramseier, and V. Makios, ????: .

Wang, X., W. Jiang, H. Xie, S. Ackley, and H. Li, 2020: Decadal variations of sea ice thickness in the amundsen-bellingshausen and weddell seas retrieved from icesat and icebridge laser altimetry, 2003–2017. *Journal of Geophysical Research: Oceans*, **125 (7)**, https://doi.org/10.1029/2020JC016077.

Webster, M., and Coauthors, 2018: Snow in the changing sea-ice systems. *Nature Climate Change*, **8 (11)**, 946–953, https://doi.org/10.1038/s41558-018-0286-7.

Webster, M. A., I. G. Rigor, S. V. Nghiem, N. T. Kurtz, S. L. Farrell, D. K. Perovich, and M. Sturm, 2014: Interdecadal changes in snow depth on arctic sea ice. *Journal of Geophysical Research: Oceans*, **119 (8)**, 5395–5406, https://doi.org/10.1002/2014JC009985.

WMO, 2019: WMO-1225. Wmo strategic plan 2020-2023. World Meteorological Organization, URL https://library.wmo.int/doc_num.php?explnum_id=9939.

Worby, A. P., C. A. Geiger, M. J. Paget, M. L. Van Woert, S. F. Ackley, and T. L. DeLiberty, 2008: Thickness distribution of antarctic sea ice. *Journal of Geophysical Research: Oceans*, **113 (C5)**, https://doi.org/10.1029/2007JC004254.

Xu, S., L. Zhou, J. Liu, H. Lu, and B. Wang, 2017: Data synergy between altimetry and l-band passive microwave remote sensing for the retrieval of sea ice parameters—a theoretical study of methodology. *Remote Sensing*, **9 (10)**, 1079–1122, https://doi.org/10.3390/rs9101079.

Ye, Y., M. Shokr, G. Heygster, and G. Spreen, 2016: Improving multiyear sea ice concentration estimates with sea ice drift. *Remote Sensing*, **8 (5)**, 397–419, https://doi.org/10.3390/rs8050397.

Zatko, M. C., and S. G. Warren, 2015: East antarctic sea ice in spring: spectral albedo of snow, nilas, frost flowers and slush, and light-absorbing impurities in snow. *Annals of Glaciology*, **56 (69)**, 53–64, https://doi.org/10.3189/2015AoG69A574.

Zege, E., A. Malinka, I. Katsev, A. Prikhach, G. Heygster, L. Istomina, G. Birnbaum, and P. Schwarz, 2015: Algorithm to retrieve the melt pond fraction and the spectral albedo of arctic summer ice from satellite optical data. *Remote Sensing of Environment*, **163**, 153–164, https://doi.org/10.1016/j.rse.2015.03.012.

Zhou, C., T. Zhang, and L. Zheng, 2019: The characteristics of surface albedo change trends over the antarctic sea ice region during recent decades. *Remote Sensing*, **11 (7)**, 821–845, https://doi.org/10.3390/rs11070821, URL https://www.mdpi.com/2072-4292/11/7/821.

Zhou, L., and Coauthors, 2021: Inter-comparison of snow depth over arctic sea ice from reanalysis reconstructions and satellite retrieval. *The Cryosphere*, **15 (1)**, 345–367, https://doi.org/10.5194/tc-15-345-2021.

Zhuang, Y., H. Jin, W.-J. Cai, H. Li, M. Jin, D. Qi, and J. Chen, 2021: Freshening leads to a three-decade trend of declining nutrients in the western arctic ocean. *Environmental Research Letters*, **16 (5)**, 054 047, https://doi.org/10.1088/1748-9326/abf58b.