KEPLER Deliverable Report

Deliverable D4.2

Deliverable name	Recommendations for improved sea ice ECV records		
Scheduled delivery	**month:** 20	**date:**	31th July 2020
Actual delivery	**month:** 23	**date:**	30th October 2020
Report type	Public Report		
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Executive summary

As part of the EU H2020 KEPLER project, we analysed the status of the Sea Ice Essential Climate Variable (ECV) and its current implementation in Europe. We thus focus on the climate monitoring of the frozen polar oceans, with the specific requirements for multi-decadal, error-characterized and time-consistent satellite-based data records.

Our analysis builds on the requirements set out by WMO Global Climate Observing System (GCOS) for the Sea Ice ECV, a gap analysis of the Sea Ice portfolio in Europe (assessing the contributions of the four main agencies or services EUMETSAT, ESA, C3S, and CMEMS), and a specific survey of the community of producers of such sea-ice climate data records.

We find that the engagement of the four main contributors cited above is an opportunity to further develop the monitoring of the Sea Ice ECV in Europe, but that their R&D and production agenda must become better coordinated to achieve the best results and increase the number of sea-ice variables serviced as state-of-the-art climate data records. The Copernicus services, ESA, and EUMETSAT can build upon the expertise of the community of sea-ice climate data producers in Europe.

Our recommendations for an improved Sea Ice ECV in the next phase of Copernicus are given in a section at the end of this report.

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Introduction

This report (D4.2 "Recommendations for improved sea ice ECV records") is an outcome of the KEPLER's (Key Environmental monitoring for Polar Latitudes and European Readiness) project and specifically investigates the Sea Ice Essential Climate Variable (ECV), focusing on Climate Data Records (CDRs) and Climate information for the sea-ice Essential Climate Variable (ECV). It is noteworthy that D4.2 builds upon the Stakeholders and Users Requirements collected in WP1, the inventory of the CMEMS multi-year products (both reanalysis and satellite-based products), and the gaps identified there (e.g. D2.2, D5.1).

This report covers several aspects, such as:

1. Introduce the WMO GCOS ECVs, and the Sea Ice ECV in particular;
2. Report on the current implementation of the Sea Ice ECV in Europe;
3. Outline ways to better serve the Sea Ice ECV from Europe (recommendations).

As part of the 3rd item above, our team conducted a consultation of the community of sea ice climate data-records producers, and we report our findings in this report.

WMO GCOS and the concept of ECVs

WMO GCOS

The Global Climate Observing System (GCOS) was established in 1992. It is a programme instigated 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 (UN Environment), and the International Science Council (ISC).

GCOS regularly assesses the status of global climate observations of the atmosphere, land and ocean and produces guidance for its improvement. Status and guidance are materialized in documents including the Adequacy Reports (1998, 2003), Implementation Plans (IP, 2004, 2010, 2016) and Progress Reports (2009, 2015). At the time of writing, the most recent IP is from 2016 (GCOS-200: https://library.wmo.int/doc_num.php?explnum_id=3417).

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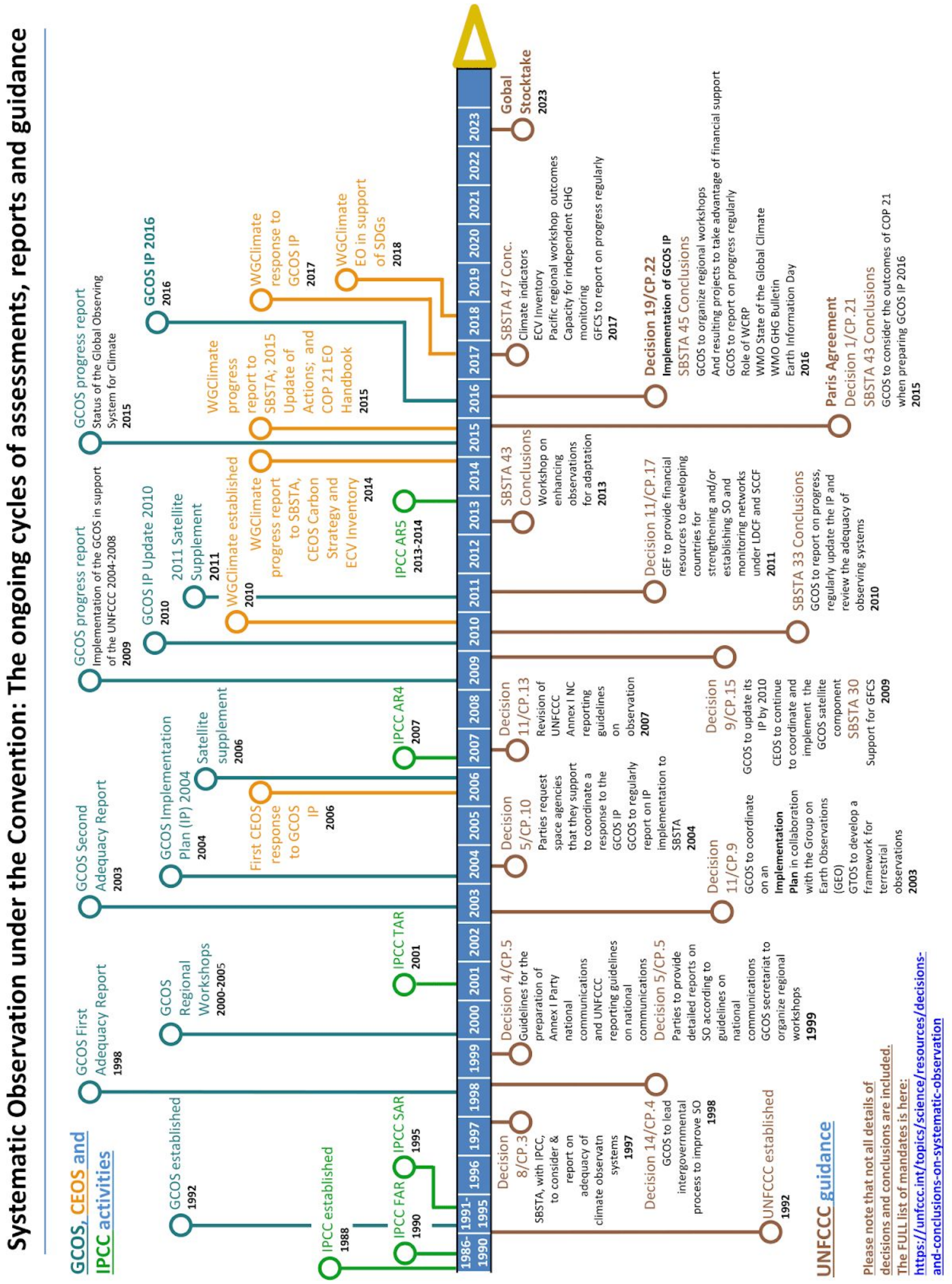

Figure 1: Timeline of interactions between GCOS (blue), CEOS (orange), and IPCC (green) activities. See https://gcos.wmo.int/en/about/UNFCCC for a higher quality version of the slide.

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GCOS reports to the United Nations Framework Convention on Climate Change (UNFCCC) in Workstream "Systematic Observations". For example, it regularly reports to the Subsidiary Body for Scientific and Technological Advice (SBSTA) progress on its Implementation Plan. As such GCOS is directly involved in the process of the UNFCCC and COP, as illustrated in Fig. 1 (https://gcos.wmo.int/en/about/UNFCCC).

The GCOS ECVs and expert panels

One of the concepts introduced and promoted by GCOS is that of Essential Climate Variables (ECVs). ECVs have been at the core of GCOS work since the start in early 1992, and was further defined and scoped by Bojinski et al. (2014). As the name suggests, an Essential Climate Variable (ECV) is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of the climate of the Earth. GCOS currently[1] specifies 54 ECVs.

Not any variable can automatically be considered a GCOS ECV: ECVs need to be relevant, feasible, and cost-effective. They thus make an impact as a UNFCCC Systematic Observation (relevance), and are measurable globally with existing technologies (feasibility) at an affordable level of investment (cost-effectiveness). ECVs are more than 'just' variables: they come with guidance and best practices (some developed by GCOS itself) to enable the generation of high-quality and traceable ECV data records that help to solve challenges in climate research, underpin climate services and support adaptation policies (Fig. 2).

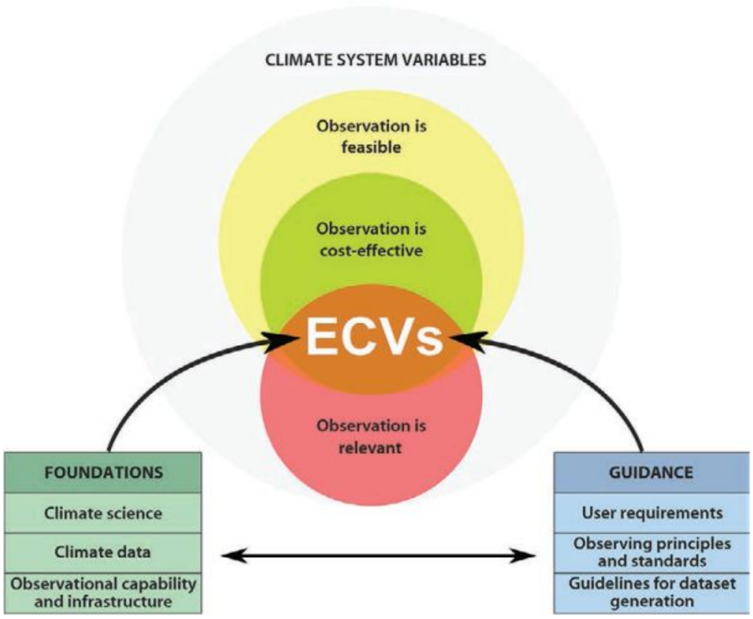

Figure 2: Schematic of the ECV concept (from Bojinski et al. 2014).

[1] as of July 2020

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Fig. 3 holds the list of the 54 ECVs defined by GCOS, organized into 3 domains (Atmosphere, Land, Ocean). Sea Ice is one of the 19 Ocean ECVs.

Atmosphere

Surface
- Precipitation
- Pressure
- Radiation budget
- Temperature
- Water vapour
- Wind speed and direction

Upper-air
- Earth radiation budget
- Lightning
- Temperature
- Water vapor
- Wind speed and direction

Atmospheric Composition
- Aerosols
- Carbon dioxide, methane and other greenhouse gases
- Clouds
- Ozone
- Precursors for aerosols and ozone

Land

Hydrosphere
- Groundwater
- Lakes
- River discharge

Cryosphere
- Glaciers
- Ice sheets and ice shelves
- Permafrost
- Snow

Biosphere
- Above-ground biomass
- Albedo
- Evaporation from land
- Fire
- Fraction of absorbed photosynthetically active radiation (FAPAR)
- Land cover
- Land surface temperature
- Leaf area index
- Soil carbon
- Soil moisture

Anthroposphere
- Anthropogenic Greenhouse gas fluxes
- Anthropogenic water use

Ocean

Physical
- Ocean surface heat flux
- Sea ice
- Sea level
- Sea state
- Sea surface currents
- Sea surface salinity
- Sea surface stress
- Sea surface temperature
- Subsurface currents
- Subsurface salinity
- Subsurface temperature

Biogeochemical
- Inorganic carbon
- Nitrous oxide
- Nutrients
- Ocean colour
- Oxygen
- Transient tracers

Biological/ecosystems
- Marine habitats
- Plankton

Figure 3: The 54 GCOS ECVs (as of July 2020).

An important aspect of the ECVs is the ECV Requirements. They are a set of numerical values defining at a high level what characteristics should be reached by the Climate Data Records (e.g. in terms of spatial/temporal resolution, accuracy, stability, etc.) to be useful contributions to improve our knowledge of the climate system. These requirements (and the list of ECVs) are set and maintained by three expert panels, one per domain: the Atmospheric Observation Panel for Climate (AOPC), the Ocean Observations Physics and Climate Panel (OOPC, co-sponsored with GOOS and WCRP) and the Terrestrial Observation Panel for Climate (TOPC, co-sponsored with WCRP).

The role of the expert panels is to maintain the list, definitions, and requirements for each ECV, and to report regularly on the status of the observing system, including on actions identified in the Implementation Plans.

Implementing the ECVs: climate data records

GCOS provides the concept of ECVs, maintains them via the expert panels, and prepares guidelines on how to generate high-standard Systematic Observations of the ECV. However, GCOS itself does not deal with the implementation of the ECVs into Climate Data Records (CDRs).

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Climate Data Records (CDRs) are the implementation of an ECV. They can be based on observations only (satellite and/or in-situ) or involve geophysical modelling (re-analyses). Because the generation of CDRs requires operating and maintaining complex processing systems (processing chains, models, etc.), they generally require specific funding. Funding agencies use the definitions of ECVs as well as their requirements as a target for implementation projects that sometimes transfer into operational services.

In Europe, examples of such implementation projects are the ECV projects under the umbrella of the Climate Change Initiative (CCI) of the European Space Agency (ESA), the climate-relevant products of the Satellite Application Facilities (SAFs) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and the Copernicus Services (currently mainly the Climate Change Service C3S, and the Copernicus Marine Environment Monitoring Service CMEMS). There are other implementation initiatives in other parts of the World, e.g. in the US. Because satellite data play a crucial role in many Climate Data Records, the initiatives are often piloted by Space Agencies.

These agencies are coordinated in the Committee on Earth Observation Satellite (CEOS), and the Coordination Group for Meteorological Satellites (CGMS). These two groups collaborate in the joint CEOS / CGMS Working Group on Climate (WG Climate). WG Climate coordinates the ECV inventory (http://climatemonitoring.info/ecvinventory) and the CEOS-CGMS Response to the GCOS IP and SS (see orange elements in Fig. 1).

These large-scale coordinated initiatives are the most visible, and surely lead to the most sustained initiatives that cover many of the GCOS ECVs. But they develop from a network of research scientists, teams, and their institutions where the core knowledge and tools reside and are continuously updated.

The Sea Ice ECV and its current implementation in Europe

The Sea Ice ECV is one of the 54 ECVs currently defined by GCOS, and one of the 19 ECVs in the Ocean domain (Fig. 3). In the latest Implementation Plan (IP-2016), Sea Ice contains 4 ECV Products: Sea Ice Concentration (the area fraction of sea ice), Sea Ice Edge/Extent (binary ice/no-ice masks), Sea Ice Thickness, and Sea Ice Drift. It is implemented in several European projects and operational services (including the EUMETSAT OSI SAF, ESA CCI, CMEMS, and C3S) and supported by an international network of research groups and institutes.

Definition and stewardship for the Sea Ice ECV

The Sea Ice ECV is a multi-variate GCOS ECV. In the latest Implementation Plan (IP-2016), Sea Ice contains 4 variables (so-called ECV Products) (see Tab 1).

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Ocean ECV product requirements					
ECV	Products	Frequency	Resolution	Required measurement uncertainty	Stability (per decade unless otherwise specified)
Sea ice	Sea-Ice concentration	Weekly	1–15 km	5% ice area fraction	5%
	Sea-ice extent/edge	Weekly	1–5 km	5 km	Unspecified
	Sea-ice thickness	Monthly	25 km	0.1 m	Unspecified
	Sea-ice drift	Weekly	5 km	1 km/day	Unspecified

Table 1: Definition and requirements for the Sea Ice ECV and its 4 Products in the GCOS IP 2016. For definitions of "measurement uncertainties" and "stability" in this context, refer to the GCOS documents.

Being an Ocean variable, Sea Ice falls under the umbrella of the OOPC expert panel that is responsible for maintaining and evolving the set of requirements. Since July 2020, the Global Cryosphere Watch (GCW, a body of WMO specialized in all aspects of the cryosphere) supports GCOS and OOPC in maintaining the Sea Ice ECV requirements.

Note: Table 1 reflects the current status of the GCOS IP (2016). The next versions of the GCOS IP will probably include more variables and updated requirements. Requirements will also be split into 3 categories (Goal, Breakthrough, Threshold).

The Sea Ice ECV in the ECV Inventory

As a contribution to UNFCC's "Systematic Observations" workstream, WGClimate (the joint CEOS and CGMS Working Group on Climate) maintains an Inventory of CDRs implementing GCOS' ECV. The inventory is available at https://climatemonitoring.info/ecvinventory/ and a third version (v 3.0) was released in July 2020, using data collected up until 2019.

The ECV Inventory is an open resource to explore existing and planned data records from space agency-sponsored activities and provides a unique source of information on CDRs available internationally. The inventory lists CDRs and Interim CDRs (ICDRs), but not Fundamental CDRs (FCDRs). Only the variables officially registered as ECV Products are listed in the inventory (e.g. existing CDRs of Sea Ice Age[2] or Sea Ice Type[3] do not enter the inventory).

There are 27 existing CDRs (incl. ICDRs) registered in the inventory for the Sea Ice ECV (14 for Sea Ice Concentration, 3 for Sea Ice Drift, 6 for Sea Ice Extent/Edge, and 4 for Sea Ice Thickness).

[2] Sea Ice Age is the (typically integer) number of years a sea-ice parcel has survived since it formed by freezing.
[3] Sea ice Type is a classification of sea ice, which can be e.g. Young, First-Year, Second Year, or Multi-Year.

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The inventory also allows agencies to register their planned (firmly committed) CDRs and ICDRs. The inventory lists 14 planned CDRs (incl. ICDRs) for the Sea Ice ECV (4 for Concentration, 1 for Drift, 2 for Extent/Edge, and 7 for Thickness).

The ECV inventory is intended to support gap analyses for individual ECVs, and to our knowledge, such gap analysis was not yet conducted for the Sea Ice ECV. The four ECV products have corresponding CDRs. Looking at the number of entries only, it would seem that Sea Ice Drift has received less attention than the other three ECV products.

Note, however, that the number of CDRs registered on the ECV inventory can be misleading regarding the coverage of individual ECV products since the respondents to the CDRs have several degrees of freedom to define a CDR entry, e.g. some will register one entry for a global CDR while others will register two (the two hemispheres seen separately).

Finally, it is recalled that currently the ECV inventory holds only CDRs for variables that are officially registered as ECV products, and can thus not be used to assess the maturity and availability of variables such as Sea Ice Age, Type, etc. , despite some of them are already part of operational catalogues (e.g. the Sea Ice Type CDR + ICDR in the Copernicus Climate Change Service (C3S)).

Current implementation in Europe

Taking advantage of continued and pre-existing development activities, Copernicus currently services all four Sea Ice ECV Products (Table 2).

	CMEMS Catalogue	C3S CDS
Sea Ice Concentration	brokered from OSI SAF	brokered from OSI SAF & CCI
Sea Ice Extent/Edge		Own (based on OSI SAF)
Sea Ice Thickness	(partly) brokered from C3S	Own (based on CCI)
Sea Ice Drift	Own (from IFREMER)	
Sea Ice Type (not a GCOS ECV product)		Own (based on OSI SAF)

Table 2: The five sea-ice variables for which CDRs are available in the CMEMS Catalogue and the C3S CDS, with the origin of the developments. Orange cells show where a variable is covered in one of the services only.

A first recommendation directly derives from Table 2: It is to facilitate the exchange of Climate Data Records that are relevant to the CMEMS and C3S services (fill the orange boxes). We suggest that the most effective way to achieve aligning the two catalogues is to implement the coordination at a

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Service-level, and that aligning the catalogues should also cover all ocean variables (e.g. Sea Surface Temperature, Sea Level, etc...).

As shown in Table 2, the mechanisms through which these sea-ice CDRs are accessible to the Copernicus users are not obvious and involve a number of non-Copernicus initiatives and services, among them the EUMETSAT OSI SAF and ESA CCI. We illustrate this with two variables: Concentration and Thickness.

Sea Ice Concentration (SIC). Both CMEMS and C3S broker the SIC Climate Data Record (and its continuous extension the ICDR) from the EUMETSAT OSI SAF. In addition, C3S distributes one from ESA CCI (no extension). In case of the OSI SAF record, the brokering is regulated by Service Level Agreements (SLA) between Météo-France (the Legal entity entrusted with the OSI SAF service) and Mercator Ocean Intl. (CMEMS) and ECMWF (C3S). The SLA is to be renewed for each major upgrade of the OSI SAF data record, and regulates among others the aspects of redistribution, crediting, documentation, and user support. The ESA CCI SIC data record is re-distributed via C3S (not CMEMS) and the ESA CCI documentation was adapted to meet the C3S template. No SLA was needed for the CCI data because the data license is less strict. The landscape for Sea Ice Concentration is illustrated in Fig. 4, sketching the various relations from the scientific Earth Observation scientists and data producers (to the left) to the Catalogue of the two Copernicus Services (middle) and to the production of Climate information (Climate Indicators, State of the Climate Report) (to the right).

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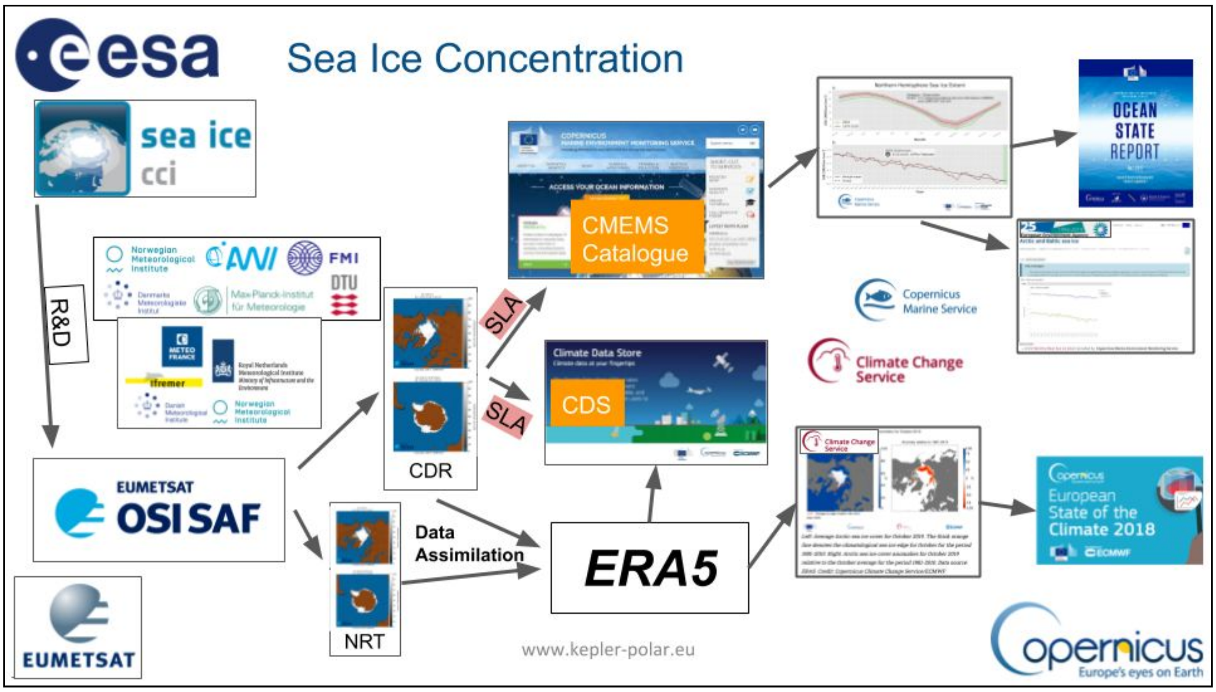

Figure 4: Tracing the Sea Ice Concentration ECV Product distributed by the Copernicus services (right, C3S and CMEMS) to the original producer services (EUMETSAT OSI SAF, with R&D contribution from ESA CCI). SLA stands for "Service Level Agreement".

Sea Ice Thickness (SIT). C3S distributes a fixed-length CDR that was produced by ESA CCI. In addition, it funds a continuous extension of the CDR (ICDR). CMEMS brokers the CDR (but not the ICDR) from C3S. Users of the two Copernicus services thus access the same SIT data source, but not covering the same period of time.

These two examples illustrate the strengths but also challenges of the current implementation of the Sea Ice ECV in Europe.

A clear advantage is that the Copernicus services were able to take on the existing Climate Data Records, use them in their value chain (e.g. in the C3S ERA5), and disseminate them to their users (once the SLAs were in place). Copernicus (C3S) could also rapidly provide data that were not available from elsewhere, e.g. by producing an operational continuous extension (the ICDR) and its own Sea Ice Type and Edge data records.

But such a mechanism also has its challenges, including:

- For the users: confusion which data are genuinely new in the Services, and which data are brokered from other sources (e.g. OSI SAF and CCI). The information is often not easily

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accessible because product identification, and documentation are modified (to accommodate the various templates).

- For the users: there is no guarantee that the data catalogues at the Copernicus services hold the latest and most accurate version of the data. Version mismatch will happen when the data producers prepare a new version of their data not yet transferred into the Copernicus Service.
- For the data producers: there is no overview of the requirements from the Copernicus users (within and downstream of the Services). Since new versions of the data records are often prepared to accommodate emerging user requirements, it is important that these requirements are timely accessible to the data producers when the data are not produced by the Service.
- For the data producers: unclarity who funds the necessary R&D to prepare new versions of the data. The "ownership" of data records and the use of open competition (ITTs) sometimes precludes pooling together funding from several initiatives for the production of a new CDR. CMEMS and C3S being operational services typically do not fund basic R&D for maturing research-based prototype variables or step-change approaches. Should this be addressed by other elements of the EU R&D funding such as Horizon Europe? Or is it a role for ESA CCI?
- For the European funding agencies: difficulty to initiate support on new sea-ice variables because there is no shared agenda or clearly defined role for the various actors. In our understanding it is the lack of planning at the funding phase that slows down the development of the ECV Sea Ice most, not the lack of research-based CDRs that could mature with proper funding..

This report does not offer solutions to these challenges but acknowledges they exist, potentially at a more visible stage for the Sea Ice ECV than for other variables (contribution by 4 non-coordinated programmes, a multiplicity of the ECV Products to be addressed, etc.). A coordination meeting between the main European actors of the Sea Ice ECV, including data producers, operational and R&D funding agencies, and key users would be a good start.

Future evolution for the Sea Ice ECV in Europe

Gap Analysis

The KEPLER project conducted a gap-analysis of the CMEMS Catalogue of Climate Data Records of the Sea Ice ECV, which was presented in D2.2 *Ways to improve the description of the changing Polar Regions in the Copernicus Marine Environment Monitoring Service (CMEMS)*, released in March 2020. Table 3 (below) is an excerpt from D2.2's Appendix 4. Only sea-ice related entries have been selected..

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D2.2 concluded that several sea-ice variables required to better characterize the polar regions are missing from the CMEMS Catalogues. These variables are also not covered in either C3S, SAFs, nor CCI. For a subset of these missing variables (Sea Ice Age, Melt Pond Fraction, Sea Ice Albedo, Lead Detection, and Snow Depth) there exist research-based prototype products that could mature to fully operational Climate Data Records if the required funding was available.

Themes	Variable (Unit)	Sat In situ	Spatial Resolution	Temporal Resolution/Target Delivery Time/Frequency/Temporal Coverage/Seasonality	Other sources In Situ Satellite	Comments
Sea Ice	SIC*	Sat	25km	D/before 12 UTC/D/(2016; -16D)/Y D/Y/Y/(1979-2015)/Y	OSI SAF EUMETSAT (with R&D input from ESA CCI)	ant + arc Nimbus 7 SMMR / DMSP SSM/I / DMSP SSMIS
	SIT*	Sat	25 km(Arc)	D/Y/Y/(2002-2015)/Y	Sat ESA CCI	brokered from C3S
	SIDrift*	Sat	62.5km (Arc)	3D+6D+M/Y/(1999-2016)/Y		ASCAT, QuikSCAT, SSM/IS
	ISTemperature*	Sat				(planned within CMEMS by 2020, details not known yet)
	SIType*	Sat	25km (Arc)	/before 12 UTC/D/(2016; -16D)/Y D/Y/Y/(1979-2015)/Y		available in C3S (not brokered in CMEMS)
	SIAge	Sat			R&D product exists	requires sea-ice drift and sea-ice concentration products.
	Melt ponds	Sat			R&D products exist	Sentinel-3 OLCI (as well asl MODIS, MERIS, VIIRS...)
	Sea ice Albedo*	Sat			R&D products exist	Sentinel-3 OLCI (as well asl MODIS, MERIS, VIIRS...)
	Ice salinity	in-situ?				
	Leads detection	Sat			R&D products exist	
	Pressure ridge size and distribution	Sat?				
	snow depths*	Sat			R&D products exist	Many techniques (microwave radiometry, altimetry, SAR,...)

Table 4: Excerpt from Appendix 4 of KEPLER report D2.2 (*Ways to improve the description of the changing Polar Regions in the Copernicus Marine Environment Monitoring Service*) focusing on ECV Sea Ice.

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It is a recommendation from KEPLER (in D2.2 already, and confirmed here in D4.2) that necessary R&D steps should be funded to mature these new sea-ice variables from the existing prototypes, and transfer them into an operational framework, i.e. CMEMS, C3S, or SAF. The needed R&D could be covered by ESA CCI, SAF, or other EU funding (e.g. Horizon Europe). It would be beneficial if such R&D effort is conducted openly and transparently that allows intercomparison between candidate algorithms and approaches, as is the standard in the ESA CCI projects.

It should be noted that R&D and operational support of the sea-ice variables already on board of the Copernicus Services (see Table 1) should continue in the future. The accuracy and relevance can always be improved, and new satellite data (e.g. those of the Sentinels, and later HPCMs) must be implemented. In some cases, progress on a sea-ice variable requires further development in another variable (e.g. better sea-ice concentration during the melt season requires advancing on the melt-pond fraction and better sea-ice thickness requires advancing on sea-ice type/age characterization and snow-depth on sea ice). These dependencies are important for multivariate ECVs like sea ice, in particular for the mutual consistency of product updates.

Needs of sea-ice data producers to improve their data products.

As part of the KEPLER project a questionnaire was prepared and sent to the community of sea-ice ECV producers (M4.2). Several topics are addressed, including the availability of input satellite data, availability of validation data, required R&D activities, and how the various European programmes and services working towards the production of sea ice ECV products (C3S, CMEMS, ESA CCI, EUMETSAT OSI SAF, Horizon Europe,...) could be better streamlined. The questions were grouped into six themes: Sea Ice: a multi-variables ECV, Sea Ice ECV requirements, access to input data, R&D needs, availability of validation data, and the landscape of sea-ice ECV programmes (with a focus on Europe).

Complementing earlier questionnaires within KEPLER (in WP1) and in several other projects, this survey focused on the data producers instead of the data users to try and understand the factors that impede or slow down the development of sea ice CDRs with a focus on Europe.

The questionnaire was sent by email to identified experts, and through relevant mailing lists including CryoList. The questionnaire is appended to this report.

We received answers from 20 scientists or research groups involved in the production of climate-relevant sea-ice data products (we directly contacted ~30 scientists, plus the distribution on the mailing lists). Of these 20 answers, 13 were from Europe, 6 from North America, and 1 from Asia. Most of the respondents did not address all the six proposed themes but rather focused on the aspects they had input to.

Below we summarize the input received on each of the six themes.

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Theme 1 : The Sea Ice ECV, a multi-variable ECV.

With this section we explored how the Sea Ice ECV is perceived especially related to it being a multi-variable ECV. The majority of the respondents provided input.

The datasets considered by the respondents and their teams covered several variables, including the four currently identified as GCOS ECV products (concentration, edge/extent, thickness, and drift) as well as others such as melt-pond fraction, sea-ice age, spectral and broadband albedo, sea-ice freeboard, snow-depth, lead fractions, polynya mapping, melt and freeze onset indicators.

Several respondents mentioned sea-ice density, sea-ice (and snow) surface roughness, sea-ice (and snow) surface temperature, and snow mass (snow water equivalent) as variables that should be considered in the context of the Sea Ice ECV.

Many of the respondents were from the sea-ice thickness retrieval community (including freeboard and snow-depth) using altimetry. Microwave radiometry was also well represented. Some groups used scatterometry. Optical radiometry (Visible / Infrared) was also presented, e.g. for melt-pond and lead fraction. No respondents used SAR data for their climate data records.

The interconnection of the sea-ice variables was emphasized by the respondents, e.g. sea-ice thickness from radar altimetry relies on knowledge of sea-ice density, type, and snow depth. In such cases, the auxiliary data products are pulled from other data providers with a subjectively preference for institutional/operational actors.

Some parameters are retrieved jointly, e.g., melt-pond fraction and sea-ice concentration, or sea-ice albedo and (thin) sea-ice thickness.

Most of the datasets are freely available online. The datasets supported by larger institutions and operational services were accessible through metadata-driven catalogues (often with DOIs), while those promoted by smaller teams and individual scientists were made accessible through FTP. The less mature datasets ("research mode") were only available "upon request".

Theme 2: Requirements for the Sea Ice ECVs.

With this theme, we wanted to learn how requirements (and in particular GCOS ECV requirements) were handled and perceived by the data producers.

To the question if they are aware of the GCOS Sea Ice ECV requirements, roughly half answered "no". Of those having answered "yes" (they are aware), half responded that the GCOS requirements did not directly influence the preparation of their datasets.

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Data producers associated with larger institutions or operational services, both in Europe and North America, were those knowing the GCOS requirements better and answered that they had taken them into account in preparing the data records.

Some comments on the existing GCOS requirements are:

- that they would benefit from being staggered as threshold / target / breakthrough requirements (which is apparently underway in preparation for the next GCOS IP);
- that many of the sea-ice variables that are relevant for climate science (see some examples above) are not recognized as ECV products (as of IP 2016) and that there should be a transparent process to “nominate” them (the KEPLER survey was conducted late 2019, thus ahead of the on-going public consultation initiated by GCOS);
- that -in any case- data records that are not listed as ECV products or do not comply with the GCOS requirements are still useful for climate science.

Theme 3: Access to input satellite data.

With this theme, we investigated whether data producers have access to upstream satellite data required for producing their data records, and whether they know of older satellite data that should be rescued to extend the coverage into the past. We also asked about potential future data gaps, and the contribution of the HPCMs (CIMR, CRISTAL, and ROSE-L).

Fundamental Climate Data Records (FCDR) are long-term inter-calibrated and quality-controlled data records of the satellite observation (L1b), like radiances, backscatters, altimeter signals. There seems to be a preference for using proper FCDRs when they exist, but several respondents use operational archives that they quality-checked themselves. Access to proper documentation (of the satellite instrument and the steps to prepare the L1b measurements) was underlined as well as the access to per-pixel uncertainties (though none reported using them directly in their processing). The free and open access license was cited by several as a ‘must-have’.

Existing FCDRs based on microwave radiometers are used in Europe and North America. Those based on scatterometers and radar altimeters are under construction (in Europe), and the sea-ice community is well aware that they will be available in due time.

For sea ice, identified past satellite missions are from the European Space Agency, especially the early scatterometer and altimeter observations of ERS-1 and ERS-2. While there is work on the altimeter record (the ESA FDR4ALT project), we are not aware of any initiative concerned with the scatterometers.

Outside Europe, data from the Electrically Scanning Microwave Radiometer (ESMR) sensor on Nimbus-5 and (possibly) Nimbus-6 missions (both pre-1978) are of interest. Data from Nimbus-5

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(1972-1977) have been available for some years in daily gridded form[4], but only recently in swath projection[5]. ESMR Nimbus-6 data is to the best of our knowledge not available online. On the Russian side (then USSR) the SHF-radiometer instruments on the Meteor satellites (at least 1974-1983, with some gaps, for the Priroda series) could also be very relevant to extend the sea-ice data record pre-1978 (concentration/extent/area), but the data is not accessible as far as we can tell.

When it comes to future satellite missions, two potential gaps are clearly identified by the respondents: conically scanning microwave radiometers (typically used for monitoring the sea-ice concentration, edge, type, drift, etc... CDRs) and high-latitude radar altimetry (typically used for sea-ice thickness).

There is a risk of a data gap in the Climate Data Records of sea-ice thickness in the high latitudes of the Arctic Ocean (> 81.5N). Altimeter data in this region is currently available from CryoSat-2 and ICESat-2. Both are scientific missions and in the case of CryoSat-2 well beyond the nominal lifetime of the satellite. The Sentinel-3 satellite carries a radar altimeter (with coverage < 81.5N) and is secured for the foreseeable future, but misses obviously quite essential regions of the Arctic for estimating the mass balance properly. The HPCM CRISTAL is an urgently needed successor for the capabilities of the CryoSat-2 mission, both in terms of reductions of uncertainty as well as for the continuity of sea-ice thickness data coverage > 81.5N.

When it comes to microwave radiometry, a gap is commonly feared when the last of the ageing U.S. Defence Satellites (DMSP) carrying the Special Sensor Microwave Imager/Sounder (SSMIS) instrument will fail. However, several other missions (similar but not identical) can be used for the continuation of the sea-ice concentration, edge, type, drift, etc. data records, including those from China, Japan, and Europe (EUMETSAT EPS-SG satellites). The respondents are well aware that the microwave radiometer HPCM CIMR will positively impact the continuation of the climate data records (better accuracy, better spatial resolution, etc...) but CIMR is not strictly-speaking a gap-filling mission.

Several respondents point to the benefit of the synergistic use of CIMR and CRISTAL to extend the existing data records and enable new variables (e.g. snow depth and density).

Theme 4: R&D needs for the Sea Ice ECV.

With these questions we surveyed which R&D needs are foreseen by the sea-ice ECV data producers, specifically if incremental improvements or radically new approaches were envisaged. We also polled on the use of Artificial Intelligence (AI) since it is an often-discussed topic among the Earth Observation communities and their funding agencies.

[4] https://nsidc.org/data/NSIDC-0077/versions/2

[5] https://disc.gsfc.nasa.gov/datasets/ESMRN5L1_001/summary

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Most of the respondents envisage incremental development steps to improve the accuracy of their climate data records. This is well in line with the current funding structure (at least in Europe) where R&D developments mostly take place in time-limited projects with well-defined statements of work, and delivery (e.g. a new, longer, better climate data record). Several respondents mentioned that funding (and research time) will be needed to improve the existing climate data records, and for example increase the maturity of the research-based prototype to a level where they can be served in operational services such as CMEMS and C3S.

In addition to the incremental steps approach, two “step-change” actions are mentioned:

- The development of a unified radiation (emissivity) and backscattering model for snow-covered sea ice is definitely needed for both retrieval and observational operators. This task, although falling into existing frameworks, should require substantial effort from the community from both modelling and observational aspects.
- The development of synergy algorithms that combine several data sources into one product. It is noted that potential synergies (e.g. altimetry together with radiometry, altimetry together with scatterometry, etc) cannot cover the whole 40+ years of satellite data, but in some cases approach the last 30 years, which qualifies for a climate data record.

We asked specifically about Artificial Intelligence techniques. Most respondents say they do not use AI at present in their climate data records, but are looking into it in other contexts. A limited number already use AI in specific parts of their retrieval algorithms (not in the whole chain), e.g. in surface classification (of the radar altimeter waveforms, or of thermal infrared images covering leads). AI is also attempted when the physically-based algorithms are not well established (e.g. snow on sea-ice from radiometry, summer thickness from laser altimeters, etc…).

The main reasons for not using AI are: a) lack of competence / knowledge, b) not enough training data are available, and c) the impression that physically-based methods have not been pushed to their limit yet, and should be improved before AI is justified. The concept of AI as a “black-box” that does not provide uncertainty estimates (which are key for modern climate data records) is also mentioned.

Theme 5: Access to validation data.

The questions under this theme explored the topic of validation data.

All respondents point at a lack of validation data over sea ice in the Arctic and even more so in the Antarctic. More observations of sea-ice thickness, snow depth, and temperature profiles are mentioned. Even in the better accessible Arctic some regions or periods are in general not covered (e.g. the fall season), but it is noted that the regions/periods where validation data are missing are generally very hard to reach even with significant resources.

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When validation data exist, they are generally not easily accessible. Large campaigns like NASA Operation IceBridge and ESA CryoVex are also encompassed here: access to quality-controlled data takes too long.

Climate data records specifically require the rescue of as many measurements as possible from earlier campaigns (including drifting buoys). Even though the findings are documented in the scientific literature, the actual data stay on local storages and are both inaccessible to the community at large and at risk of loss.

The issue of spatio-temporal scales is acknowledged: there is a perceived lack of understanding of how to rescale point-wise measurements (e.g. a snow pit) to an airborne track and/or to a satellite pixel. Campaigns dedicated to studying such “up-scaling” are called for (the on-going MOSAiC campaign might provide some answers here).

Specifically for sea ice, its motion is problematic. Tools should be developed and made available that can advect on-ice measurements (e.g. using model-based or satellite-based sea-ice drift products) to allow spatio-temporal collocation with asynchronous airborne or satellite-borne observations.

The sea-ice community sorely lacks a single point of access to quality-controlled, re-formatted, metadata-aware in-situ data both from the Arctic and the Antarctic (‘one-stop shop’). The efforts of formatting, re-projection, quality-control and collocation are currently left to the individual teams, which is neither transparent nor efficient. The Sea Surface Temperature community (Group for High-Resolution Sea Surface Temperature - GHRSST) is cited as an example of greater maturity in that respect.

Specifically for Copernicus, a Europe-based polar (sea ice) in-situ data portal is requested, building upon the in-situ Component itself (insitu.copernicus.eu) or in-situ services in CMEMS and C3S. At present, only “blue/green-ocean” in-situ data are covered by CMEMS. When such a service starts, it is important that it is rapidly fed with past data, to serve the climate monitoring community as well. Due to the dynamic nature of sea ice, a spatio-temporal collocation service at the data portal that takes into account the sea-ice drift (e.g. using CMEMS satellite and/or model ice drift) would be an asset.

Theme 6: The landscape of sea-ice ECV programmes.

The sixth and last theme explored the organization of sea-ice ECV servicing (and funding), with a focus on Europe (Copernicus, ESA CCI, and EUMETSAT SAFs).

Respondents to our survey were a mix of scientists engaged in nationally-funded research projects and others already contributing to the European operational services. The answers from the two groups were quite different.

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Scientists developing climate data records outside the existing operational services seek funding to sustain the production (including full reprocessing) of their time series, and servicing on well-exposed data portals to reach more users. The reprocessing step is an important one. National funding, e.g. from national space agencies, is often focused on using the new satellites, but in the context of an ECV it is key to connect the new satellites to the earlier ones, and this often requires reprocessing of long time series.

On the contrary, the groups that are already part of the operational services seek funding for continued R&D for the algorithms. They note that the current situation in Europe, with at least four heavyweight actors working on the Sea Ice ECV, is an opportunity but also a challenge as the operational production and research agendas are not coordinated.

Discussion

The Sea Ice ECV encompasses a wide variety of geophysical variables, requiring a number of different Earth Observation sensors and techniques to observe them. Some of these sub-variables are ice extent and area, ice concentration, ice thickness, ice motion, ice type (first year, multi-year) and age, ice salinity, snow cover depth, surface freeze-up and melt time, melt pond coverage, ice albedo, etc. For several of these variables, trends have been observed over the 40+ years of satellite (and buoy) observations available. Fig. 5 illustrates an excerpt from the Summary for Policy Makers (SPM) of the UNFCCC IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC SROCC, 2019). It outlines the most relevant sea-ice trends that cover 4 variables: sea-ice concentration (used to compute sea-ice extent), sea-ice thickness, sea-ice type, and sea-ice age.

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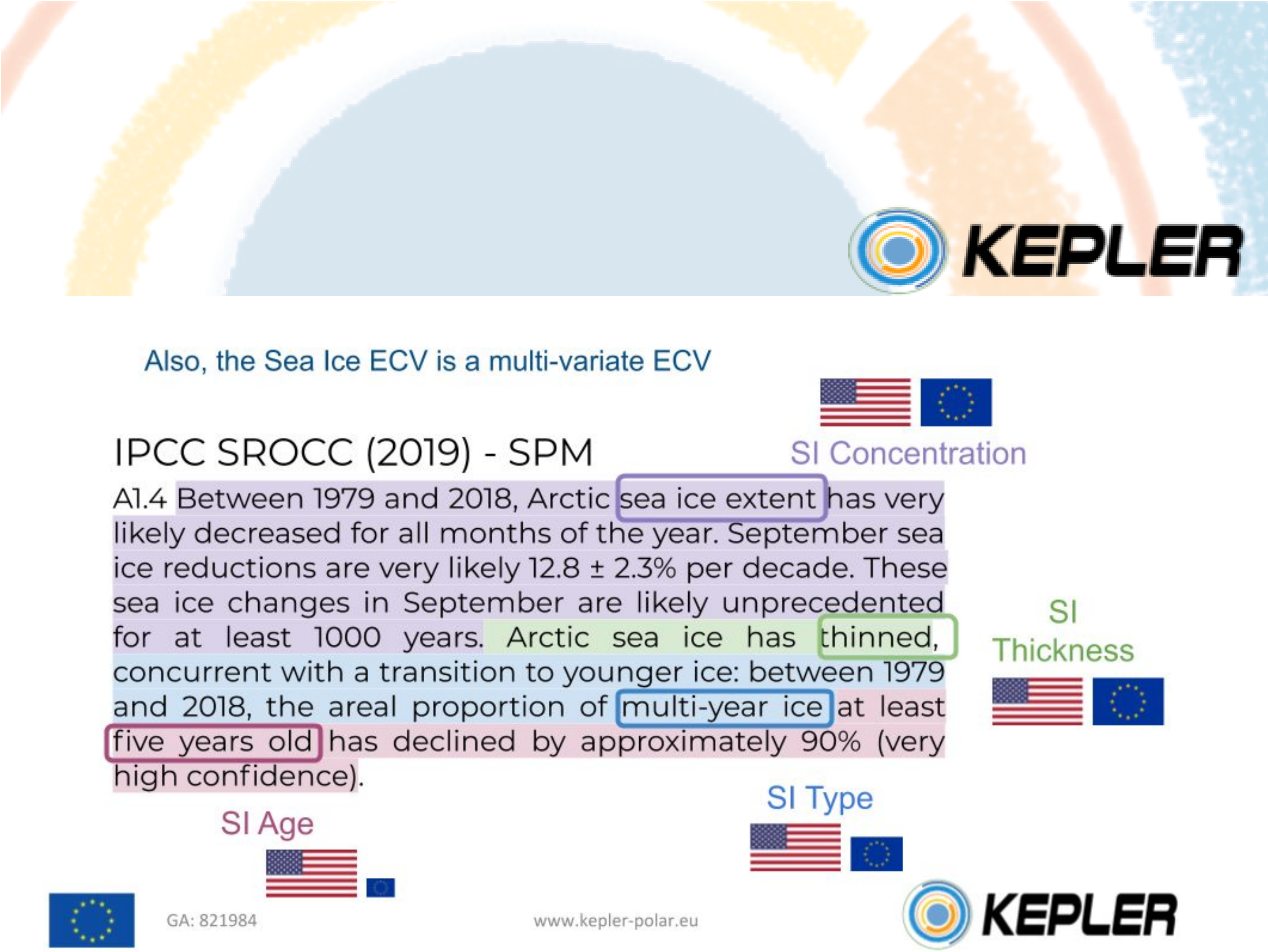

Figure 5: The sea-ice relevant content of the Summary for Policy Maker SPM in the UNFCCC IPCC Special Report on Ocean and Cryosphere in a Changing Climate (IPCC SROCC). Four sea-ice variables are contributing, and a qualitative assessment of the relative contributions from the USA vs Europe is suggested.

In Fig. 5, a subjective representation of the relative contributions from the USA (NOAA, NSIDC, NASA, etc…) and Europe (OSI SAF, CCI, CMEMS, C3S) are reported (size of the American and European flags). For Sea Ice Concentration and Thickness the level of maturity in Europe is similar to that in the USA, but Europe is still behind in terms of Sea Ice Type and Age. As in other aspects of climate research, international cooperation (including between the USA and Europe) is key for satellite-based CDRs (e.g. access to the raw satellite data, sharing of experience), but some competition is also beneficial to bring the algorithms forward and to question / confirm observed trends. For example, there is today only one CDR of Sea Ice Age (US NSIDC) and a counterpoint / confirmation from Europe would be relevant (a first effort was conducted in ESA CCI Phase 2, but not continued in CCI+ because of limited funding).

As noted in other KEPLER deliverables (e.g. D2.2) and by the responders to our survey, a key limitation to advance on polar monitoring (including sea ice) is the lack of in-situ data. Some in-situ data exist, but the deployment of the drifters and sensors is not sufficiently coordinated, and the data reside on a network of data portals. In the US, the IABP integrates the trajectories from many drifters, but not all data is there (e.g. temperature profiles in the ice and snow), and it is not an operational service Copernicus can build upon. A recommendation from KEPLER is thus to advance

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towards a central Copernicus in-situ portal holding polar (including sea ice) observations. For the purpose of monitoring the changing climate, this report further recommends that the new portal does not only consider the NRT data stream, but also ingests as many re-processed and past in-situ campaigns as possible.

Most satellite-based CDRs begin in October 1978, with the start of the Nimbus-7 mission carrying the Scanning Multichannel Microwave Radiometer (SMMR) sensor. October 1978 is considered the start of the modern satellite era. However, a limited number of satellites flew over the polar regions earlier, and with instruments that are relevant for sea-ice monitoring. These include the ESMR instruments on board the US Nimbus-5 (1972-1977) and Nimbus-6 satellites (June 1975 - August 1977). In addition, multi-frequency microwave radiometer data from SHF instruments on board Soviet Meteor Priroda missions (1974 - 1983) could extend several sea-ice variables (mainly concentration and extent) back to the early 1970s.

Unfortunately, only the ESMR Nimbus-5 data was so far rescued from tape and prepared in a digital format allowing for algorithms development and data processing.. The Sea Ice CCI+ project of ESA (2019-2021) is currently working to prepare a 1972-1977 data record of sea-ice extent from this raw data. Both ESMR Nimbus-6 and the SHF data are apparently still in the form of analog print-outs directly from satellite acquisition (if not lost). Time is ticking to retrieve and secure such precursor satellite data before data, expertise, and documentation are lost. Note that even when analogue versions of the data are localized, the process of digitization (including calibration, geo-location, and quality control) remains an immense endeavour, that should be weighed against the impact of securing a handful of years prior to the modern satellite era.

Other reports in KEPLER (e.g. D3.3 section 3 and 4) discussed at length the merits of the three polar High-Priority Candidate Missions (HPCMs) (CIMR, CRISTAL, and ROSE-L) for advancing our monitoring and understanding of the polar regions. In this report, we can examine in further detail the foreseen contribution of these three missions to the monitoring of sea ice as an ECV. When it comes to future satellite missions, two potential gaps are clearly identified by the respondents: conically scanning microwave radiometers (typically sustaining the sea-ice concentration, edge, type, drift, etc. CDRs) and high-latitude radar altimetry (typically used for sea-ice thickness). CRISTAL would be a new capability in Copernicus, but as far as climate monitoring is concerned it is also sorely needed as a successor for the capabilities of the CryoSat-2 mission (radar altimeter observations at high latitudes > 81.5N).

When it comes to microwave radiometry, the capability at coarse resolution is already secured by future operational missions such as EUMETSAT EPS-SG. CIMR is not strictly speaking a gap-filling sea-ice mission but is well identified by the community as contributing with higher resolution (e.g. regional) monitoring of the changing sea-ice cover. Several respondents point at the synergies between CIMR and CRISTAL to improve on several critical variables, such as snow depth and density.

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Because only a small number of climate data records use SAR data, and even less so at L-band, ROSE-L is not considered a critical mission for climate monitoring of the sea-ice cover.

Conclusions and Recommendations

This report explored how the Sea Ice Essential Climate Variable is currently monitored in Europe, with a focus on the Copernicus Services (CMEMS and C3S) and other contributing agencies (incl EUMETSAT OSI SAF and ESA CCI). We first recall what WMO GCOS is, its mandate and role with regards to UNFCCC, and how it defines ECVs.

The Sea Ice ECV is a multivariate ECV and we described how it is implemented by the World's space agencies (using the CEOS / CGMS joint WGClimate ECV inventory) and specifically in Europe (CMEMS, C3S, OSI SAF, and CCI).

We also polled the community of sea-ice data producers via a detailed survey to uncover what they saw as barriers for continuing and improving monitoring the sea ice ECV. The survey covered 6 broad themes and was answered by ~20 research scientists.

An analysis of the current state of the Sea Ice ECV, its implementation as far as Europe is concerned, and the replies to our survey lead us to the **following recommendations for improved Sea Ice ECV records in Europe** and in particular in Copernicus.

Recommendations:

- "The Sea Ice ECV is more than Concentration and Thickness": **Recognize that the Sea Ice ECV is multi-variate and allocate enough funding to its development** so that all ECV products, and all EO technologies, can mature. All ECV products (even the more mature sea-ice concentration and thickness) need repeated cycles of R&D. At any given time, some key sea-ice variables (see next item) might not be recognized as official ECV Products by GCOS. These nonetheless require R&D efforts to mature and later become ECV Products.
- Some key missing variables (or variables from which renewed R&D is needed) are: **melt-pond fraction** (in support to Sea Ice Concentration during the summer season), sea-ice **age/type** (ideally considered jointly), **snow-depth** (in particularly in support to sea-ice thickness retrievals), **albedo**, and **lead fraction.** Climate data records of **sea-ice drift** exist or are being prepared, and new R&D cycles will be needed to further mature them.
- Of the three Copernicus expansion polar missions, **CRISTAL and CIMR** have the highest potential to extend the monitoring of the changing polar sea ice. With the current time line with launch dates at the end of the 2020s, we must expect gaps to current missions (e.g. CryoSat-2, SMOS,...). **The gaps between missions should be made as short as possible**.
- **Within Europe, coordinate the R&D and production agendas of the main Sea Ice ECV actors (EUMETSAT, ESA CCI, C3S, and CMEMS).** There is enough work for all actors but the (perceived) lack of coordination makes it difficult to perceive which R&D is committed by the

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different agencies. The teams and institutions that actually perform the R&D and production under contract for the funders should also be invited to the coordination. We suggest organizing **an open workshop on "*monitoring the Sea Ice ECV in Europe*" to gather funding agencies, the production services, and the research community at large (including key users) to prepare a roadmap**.

- **Within Copernicus (CMEMS and C3S), synchronize the data and service catalogues of Sea Ice ECV observations between CMEMS and C3S.** CMEMS and C3S together cover the four variables of the GCOS ECV, but the catalogues are not synchronized and it is more difficult for the users to 1) find the data, and 2) trace it to the original producers.
- **For Copernicus services CMEMS and C3S: gather and make available ECV product requirements that are specific to their use area** (including assimilation in current and future re-analyses and downstream applications) and that go beyond the requirements of GCOS (e.g. higher spatial resolution, shorter latency, swath-based products). This will allow designing ECV products fulfilling the requirements of Copernicus.
- **Europe lacks a coordinated collection of in-situ validation data in sea-ice-covered regions**. The In-Situ TAC of CMEMS does not hold such data. For the purpose of validating ECV products, a focus of the in-situ service should be the temporal extent of the catalogue, and a strict quality control (rather than timeliness). **Tools should be developed and made available** that can advect on-ice measurements (e.g. using model-based or satellite-based sea-ice drift products) to allow **spatio-temporal collocation** with asynchronous airborne or satellite-borne observations.
- **Satellite data rescue should be conducted as an international endeavour to extend ECV time-series back in time.** The archives of heritage satellite missions should actively be unearthed, digitized, and quality controlled, because time is pressing to save such early data from being damaged or erased. For the Sea Ice ECV, satellite missions such as ESMR Nimbus-6 (USA), and SHF Meteor-Priroda (Russia), both of the mid-1970s, should be rescued. In Europe, retrieve and calibrate the early Scatterometer and SAR data from the ERS missions; such activities can be coordinated between C3S, ESA, and EUMETSAT. Internationally, the CEOS CGMS WGClimate has a role to play. **Fundamental Climate Data Records should be prepared once the data are rescued.**
- Many aspects of the sea-ice and snow radiation emissivity and scattering are still poorly observed or modelled. This greatly limits our ability to progress in developing improved satellite algorithms and improve the accuracy of the Sea Ice ECV products. **Continue the development of fully-fledged yet efficient emission and scattering models for sea-ice and snow**. Community models -such as SMRT- should be preferred, ideally coupled and reconciled with radiative transfer models for the atmosphere and ocean surface. This activity fits well the preparation for the High Priority Missions (CIMR, CRISTAL, and ROSE-L).

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The recommendations outlined in this section are only a highlight of the material collected during this activity, and we refer the reader to the body of the report for additional recommendations.

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Annex: Questionnaire

Replies were received from scientists at LEGOS (France), FMI (Finland), University of Hamburg (Germany), DMI (Denmark), CNES (France), University of Tromsø (Norway), University of Trier (Germany), KNMI (Netherlands), AWI (Germany), ICM/CSIC (Spain), Chalmers University (Sweden), University of Bremen (Germany), DTU (Denmark), McGill (Canada), CCAR Colorado (USA), NSIDC (USA), NOAA (USA), NASA GSFC (USA), Tsinghua University (China).

Questionnaire towards the community of sea-ice ECV records producers

in the context of the EU KEPLER project

Introduction

KEPLER (https://kepler-polar.eu/) is an initiative built around the Copernicus Services and the European Ice Services to prepare a roadmap for Copernicus to deliver an improved European capacity for monitoring and forecasting the Polar Regions. KEPLER aims at assessing the polar observational needs of the weather, ocean, sea ice, land, and climate science communities, and how these will develop over the next 10 years and beyond. The outcomes of KEPLER will be used by the European Commission to help guide the development of its Earth monitoring program: the Copernicus Services, and to help develop future research funding calls related to the polar observing

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system.

By answering this questionnaire you and/or the institution you represent can have your say in these strategic considerations for the future evolution of the polar observing system and services.

Recognizing the central role of monitoring the changing sea ice conditions in the polar regions, this questionnaire targets the producers of sea-ice Essential Climate Variables (ECV). Through a series of questions organized into six themes, the questionnaire aims at gathering a faithful picture of the community of sea-ice ECV records producers, what is working and not working today, and what would be needed to produce more (and better) sea-ice ECV records in the future. The responses we collect will be analyzed and summarized into a report to the EC: *D4.2 Recommendations for improved sea ice ECV records*.

Although the KEPLER initiative stems from Europe, we welcome contributions from the sea-ice ECV producers at large, since the description of the Earth state and climate is truly an international endeavour.

By choice, this questionnaire leaves room for free text and additional comments you may have.

The KEPLER Team thanks you for taking the time to answer.

Acronyms and Definitions

In this section, we define some terminology used in the questionnaire.

WMO GCOS: The Global Climate Observing System of the World Meteorological Organization

ECV and EOV: Essential Climate Variable and Essential Ocean Variable. ECVs and EOVs will typcally hold several “products”. For example, sea-ice concentration, drift, thickness are all “products” of the Sea Ice ECV. “products” is the GCOS terminology. In this questionnaire, we sometimes use “sub-variable”.

CDR: Climate Data Record (note: in this questionnaire, CDR englobes fixed-length CDRs and Interim CDRs).

ICDR: Interim CDRs are delayed-mode extensions of the CDR. They use the same algorithms than the CDR, but are potentially applied on different data streams.

FCDR: Fundamental Climate Data Record (homogenized and calibrated data record of Level-1 satellite data).

Latency: delay with which new data are added to the records. For example yearly updates of the ICDR has a latency of 1 year. Some ICDRs have shorter latencies measured in days (e.g. 16 days).

EUMETSAT OSI SAF: The Ocean and Sea Ice Satellite Application Facility of the European

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Organization for the Exploitation of Meteorological Satellites.

ESA CCI: The Climate Change Initiative programme of the European Space Agency

NASA MEASURES: The Making Earth System Data Records for Use in Research Environments (MEaSUREs) programme of the National Aeronautics and Space Administration

EU C3S and CMEMS: European Union's Copernicus Climate Change Service (climate.copernicus.eu) and Copernicus Marine Environment Monitoring Service (marine.copernicus.eu)

Theme 1: The Sea Ice ECV, a multi-variable ECV.

The Sea Ice Essential Climate Variable encompasses a wide variety of geophysical variables ("products"), requiring a number of different Earth Observation sensors and techniques to observe them. Some of these sub-variables are ice extent and area, ice concentration, ice thickness, ice motion, fast ice, ice type (first year, multi-year) and age, ice salinity, snow cover depth, surface freeze-up and melt time, melt pond coverage, ice albedo.

What sub-variable(s) do you or does your team produce? You may also specify the satellite sensors used, the time period covered, funding source, doi, etc…

Is your data record freely accessible online? Available upon request? Under development?

Does the retrieval of your sub-variable relies on another (sea-ice or not) ECV, and how did you manage the inter-dependency.

By definition, ECVs must be relevant, feasible, and cost effective. Are some sea-ice variables missing from the list above, that should be taken on board the Sea Ice ECV?

Theme 2: Requirements for the Sea Ice ECVs.

For all defined ECVs, the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO) manages a catalogue of requirements. These requirements are expressed in

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terms of Frequency (Temporal resolution), Spatial resolution, Required Measurement Accuracy (2-sigma), and Stability (e.g. per decade). These requirements should guide the development of ECV data products and are often the base for funding activities (e.g. the ESA Climate Change Initiative). Other use-cases for ECV data products (e.g. assimilation in re-analyses, up-to-date climate services) might have other requirements, different or on top of those of GCOS.

Are you aware of the GCOS requirements for the data record(s) you produce? Do/did they influence the development of your data record? *Do you have any other comment on requirements (GCOS or other) for the sea-ice ECV?*

Theme 3: Access to input satellite data.

It is generally accepted that long-term, inter-calibrated time-series of “raw” (Level-1B) satellite data (the Fundamental Climate Data Records, FCDRs) are a prerequisite to the production of high-quality ECV data records. As noted above, the Sea Ice ECV has many sub-variables, requiring different types of satellite sensors (microwave radiometry, visible/IR radiometers, scatterometers, altimeters, SARs,...). Access to early satellite missions (typically < 1980s) can also be challenging.

Do/did you use FCDRs as inputs to your data records? If “yes” which ones, if “no” why not? *Do you have general or specific requirements for FCDRs that are used to produce the sea-ice ECV? Please also include considerations on the provision of uncertainties.* *Is your sub-variable observed by an early satellite missions for which raw data is unavailable or difficult to access, and would require a Data Rescue activity? If yes, please specify.* *In terms of future candidate/planned space missions (until 2040) is there a risk of discontinuity or gap in the observation capabilities of your ECV record(s)?*

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Will your ECV record benefit from one of the polar Expansion missions to the EU Copernicus Space Component (microwave radiometer CIMR, dual-frequency radar altimeter CRISTAL, L-band SAR ROSE-L) or Extension missions to the already existing Copernicus satellites (Sentinel-NG: Next Generation)?   *Do you have any further remarks on the topic of access to input satellite data?*

Theme 4: R&D needs for the Sea Ice ECV.

Of the long list of sea-ice sub-variables introduced, only a handful are covered by mature, sustained ECV data records (e.g. sea-ice concentration/extent/area, thickness, type) while others have few or no reference data records yet. This can indicate that the latter sub-variables have not received enough attention, and that some R&D efforts are missing to bring them to a higher maturity level. This can also indicate that R&D funding is spent on too few of the sub-variables, and does not cover the others. A step change in Earth Observation could be the advent of Artificial Intelligence (AI).

How would your sea-ice ECV record(s) benefit from additional R&D? Can you estimate if the required R&D must aim at a) a series of incremental improvements to existing algorithms, or b) a completely new methodology to allow much better results?   *Do you use Artificial Intelligence (AI) techniques in the R&D and/or production of your ECV data product? If "yes", what AI methods and what task(s) did you solve with AI? If "no", is it due to a lack of expertise and access to tools, or because AI would not be appropriate, or are you planning to use AI?*

Theme 5: Access to validation data.

Mature ECV data products must be thoroughly validated before they are used in climate research and downstream applications, and also in the process of preparing improved versions (algorithm improvements). The scarcity of in-situ validation data in the Arctic and polar regions is well

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acknowledged and addressed in several work packages of KEPLER, and other EU projects. In the Arctic, collaboration and data sharing are key. Specific to the validation of ECV data products is the additional requirement for long archives of validation data (in-situ or other Earth Observation missions).

Do/did you have access to sufficient validation data to characterize the accuracy of your ECV data product(s)? What types of validation data would have been beneficial? Does this validation data exist but was not available to you?

Do you have any other comment on validation and/or access to validation data?

Theme 6: The landscape of sea-ice ECV programmes.

The Sea Ice ECV has long been recognized as an iconic indicator of climate change, and many ECV data records have been developed throughout the years. Still, as noted above, not all sub-variables from the Sea Ice ECV are covered with mature and operationally sustained data records. This is despite of several existing ECV programmes (e.g. EU C3S, EU CMEMS, EUMETSAT OSI SAF, NASA MEASURES...) and research initiatives (ESA CCI, federal and national research funds,...). Cost-effectiveness and non-duplication of efforts require a tight coordination between those programmes and initiatives.

Is your sea-ice ECV record produced within the context of an operational climate service (e.g. EU C3S, EU CMEMS, EUMETSAT SAF), ESA CCI or NASA MEASURES? If "no", what is/was your main source of funding?

Are your sea-ice ECV records registered at the WGClimate ECV Inventory (http://climatemonitoring.info/ecvinventory/)?

Do you have suggestions how the various ECV programmes and services could be improved towards better sea-ice ECV data products, including how development and operations are funded?

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Concluding remarks.

The responses we collect here will be analyzed and summarized into a report to the EU: *D4.2 Recommendations for improved sea ice ECV records*. Should you have concluding remarks or recommendations that do not fit into the categories above, please feel free to share them below.

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