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Context of deliverable within Work Package

This report addresses European capabilities to provide sea-ice forecast products on spatial scales from kilometers to ocean basins, and on time scales from days to seasons. We provide an overview of the current status, identify the most important gaps, and make recommendations on research and development efforts needed to progress towards more reliable and user-relevant sea-ice forecast products. This task draws on and complements the two tasks on sea-ice mapping in the same work package.

Recommendations for more user-relevant sea-ice forecasts

Executive summary

Forecasts of basic sea-ice properties like sea-ice concentration, sea-ice thickness, and sea-ice drift are available from CMEMS and C3S. These forecasts are produced with numerical forecast models that simulate the large-scale physical processes in the atmosphere, sea ice and ocean and cover the time range from days to seasons ahead. However, user uptake of these forecasts seems to be poor. In this report, we aim to understand better why this might be the case and make recommendations on how to make sea-ice forecasts more relevant for end-users.

The first and foremost gap between what users require and what current sea-ice forecasts are able to deliver is **spatial resolution**. Users often report the need for information products with a spatial resolution of 300m or better, but current numerical forecasting models are only able to provide spatial resolutions of a few kilometers at best. There is a range of scientific and technical reasons why it is not feasible to improve the spatial resolution of numerical forecasting models to the decameter scales required, but there are other ways of potentially bridging this gap:

For short-term forecasts (less than a few days ahead), *hybrid approaches* are promising, which produce a forecast by combining high-resolution satellite observations with low-resolution model fields (e.g. advecting a SAR scene with the numerical sea-ice drift field forecast). For forecasts longer than a few days ahead, low-resolution numerical forecasts could be made more useful by providing *probabilistic information about small-scale ice features on a relatively coarse grid.* Finally, high-resolution sea-ice forecasts for small regional domains could be produced by embedding *sea-ice models capable of representing the sea-ice physics at floe scales* into a low-resolution numerical forecast.

Whereas the hybrid and probabilistic approaches could lead to considerably improved products within a few years with well plannable additional resources, developing a new class of sea-ice models capable of realistic decameter-scale forecasts is a long-term research activity that requires substantial resources and has an uncertain chance of eventual success.

The second major obstacle for more user-relevant sea-ice forecasts today is a range of deficiencies in **forecast quality and presentation**. Whereas there is ample documentation of the fact that current numerical forecasts have some measurable skill in predicting large-scale sea-ice presence days to seasons ahead, the level of skill varies strongly depending on the forecasting system, the target region and season, and the spatial scales considered. Extracting the skill from the raw model output

often requires advanced forecast calibration and postprocessing techniques. It is essential to present the user with an estimate of *forecast uncertainty derived from past forecasts and forecast ensembles* as an integral component of any forecasts, so that the user can make an informed decision whether the degree of uncertainty is acceptable for the concrete decision at hand. This would also counteract a generic loss of users' trust in forecasts that can result from insufficiently conveyed uncertainties.

We recommend a stronger emphasis on assessing forecast quality against *user-relevant forecast targets*, e.g. verifying forecasts against ice charts instead of passive microwave satellite observations as is often done. This should lead to the *co-development of sea-ice forecast information products,* where sustained interaction between forecast producers and users ensures that the information products developed are fit for purpose. We believe that research and development activities regarding forecast quality and presentation promise a high return on investment in the short-to-medium term, as they only require slightly better coordination and collaboration between relevant actors and can directly build on already existing expertise and tools.

Of course, for targets where current sea-ice forecasts genuinely do not have useful quality, even in a well-conceived and user-relevant presentation, it is essential to further develop numerical forecast models, data assimilation methods and relevant observations in order to gradually improve forecast quality. However, it needs to be acknowledged that there are inherent physical limits to what can be predicted, even if the forecast model and initial conditions were perfect.

The third major discrepancy between user requirements and current capabilities is which **sea-ice properties** are provided by current numerical forecasts. While basic properties like mean concentration and thickness are provided, important properties are missing that are required by users who operate close to or in the ice. These properties include for instance compression (ice pressure), the presence of pressure ridges, stage of development, and the accurate location of the ice edge. There is some limited scope for sea-ice models used in current numerical forecasting systems to provide at least probabilistic information on some of these (e.g. area fraction of ridged ice). It might also be possible to provide some user-relevant sea-ice properties that can not be directly modelled by means of proxies with sufficient quality (e.g. derive a proxy for ice compression from ice drift). However, explicit and high-quality representation of decameter-scale sea-ice properties will only be possible with the new class of sea-ice models referred to above.

We conclude by pointing out that a sustained and constructive dialogue between the forecast producers and the forecast users (both intermediate and end-users) is the basis for achieving any progress towards more user-relevant sea-ice forecasts. We therefore recommend that research and development activities addressing sea-ice forecast skill and products are planned such that the active involvement of both parties is ensured (co-production).

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Highlight recommendations for Copernicus Services

We would like to highlight here as a bullet list some recommendations from Section 5 of this report on how to evolve the Copernicus Services in order to make sea-ice forecasts more user-relevant:

- Provide a comprehensive set of past forecasts to facilitate thorough assessment of forecast quality and allow calibration of forecasts
- Provide a multi-year archive of user-relevant sea-ice observations in a format easily accessible to forecast producers
- Provide ensemble forecasts to quantify forecast uncertainty and probabilities of occurrence
- Provide additional sea-ice properties where possible
- Stimulate/initiate research on bridging the gap in spatial resolution with hybrid approaches and probabilistic subgrid-scale information
- Stimulate/initiate co-development of information products between forecast producers and users
- Set up training activities for intermediate and end-users on the use and interpretation of forecast products including their uncertainties
- Stimulate/initiate research on decameter-scale sea-ice modelling and data assimilation capabilities

1. Introductory remarks

Forecasts are about the future, and they are inherently more uncertain than observations. This might be an obvious point, but it appears to be sometimes overlooked in the operational sea-ice community. Forecasting sea-ice conditions a few hours to at most a few days ahead (nowcasting and short-range forecasting), might be possible using only the latest observations combined with statistical modelling, but for any forecast longer than that, the complex nonlinear interactions between the atmosphere, sea ice and the ocean underneath are best modelled by explicitly representing the large-scale physical processes.

There are inherent limits how far in advance sea-ice events can be predicted, depending on region, season, sea ice property, and the spatial scale considered. Additionally, numerical forecast models have biases and errors, and initial conditions are never perfectly known. These two aspects are routinely addressed in research by the forecast producers and the natural science community in general. They result in estimates of predictability limits of certain events, and an assessment of forecast quality for any given forecasting system. The two aspects of forecast quality that are probably most important for users are the forecast sharpness, which measures if the forecast outcomes actually vary for each case, and reliability, which demands that - on average - the forecast outcome is consistent with the observed outcome. These aspects are symbolised by the left-hand set of research and development activities depicted in Figure 1.

What matters for the user is the utility or value of a forecast, i.e. whether the forecast helps the user to make a decision. This question is addressed by research and development in the user community, or among researchers more concerned with economics and policy. This set of activities is depicted on the right-hand side of Figure 1. In order to make sea-ice forecasts more user-relevant, both communities need to come together and develop a sustained dialogue on what is important and useful. If this dialogue is lacking, both communities will develop independent but inconsistent approaches to interpret and work with the forecasts, which is inefficient and blocks progress towards more user-relevant sea-ice forecasts. To some extent, this seems to be the case in the current landscape of sea-ice forecasting activities.

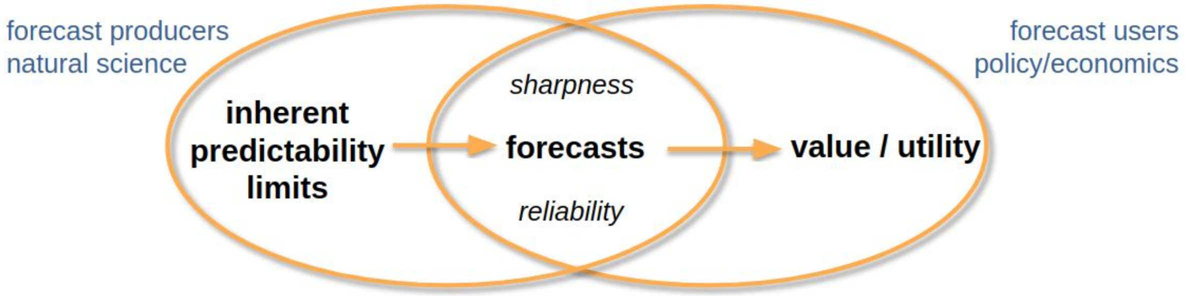

Figure 1: Venn diagram depicting forecast producers and users with different but partially overlapping interests, tools etc. Sustained interaction of forecast producers and forecast users is required to make sea-ice forecasts valuable.

A final introductory remark we would like to make is that forecast quality is highly scale-dependent: it decreases with forecast lead time (i.e. the time interval between the initialization/distribution and the target time of the forecast) and spatial resolution. This forecast quality reduction is universal, but it seems particularly problematic for sea-ice forecasts: numerical forecast models are developed and tested at scales of 10 - 100 km and days or even months into the future, while the majority of demand for better sea-ice forecasts appears to be on tactical scales, which require spatial resolution of 300m or better and lead times of two days or less. By their very nature, numerical forecast models are not well-suited to fulfil these demands. However, for planning purposes, coarser resolution of sea-ice forecasts might be acceptable, and lead times of several days or weeks might be considered.

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2. User requirements

Here, we highlight some key user requirements that are relevant to sea-ice forecasts. We draw on earlier documents (IICWG 2019, Jeuring and Knol 2019, Wagner 2019) and group requirements according to anticipated recommendations. Please refer to KEPLER deliverable report D1.1 for more details.

It is important to acknowledge that there is a wide range of user requirements, which are sometimes in conflict (e.g. requiring very high resolution and very low data volume at the same time (IICWG 2019)). Here, we focus only on the requirements that are most widely reported. Where these cannot be met by current capabilities, there is an obvious need for further research and development. We do not attempt to provide an exhaustive overview of requirements, or weigh them by economic or societal benefit.

Any useful sea-ice forecast information product needs to satisfy four basic requirements: (i) it needs to cover the time and location of interest to the user and provide sufficient spatial and temporal resolution, (ii) it needs to provide the required properties of the sea ice cover, (iii) it needs to be based on a forecast of sufficient quality, and (iv) it needs to be presented in a form that the user can easily understand and integrate into their workflow, and it needs to be communicated to the user on time using the technical means available. We spell out these requirements in more detail in the following paragraphs.

2.1 Information product resolution and coverage

The single most prominent requirement from all user surveys over the last 15 or so years is the demand for higher **spatial resolution** in information products (Wagner 2019). In the end, users operate at a specific location, and since sea ice properties can vary dramatically on spatial scales of a few meters, information products ideally need to resolve these variations. An acceptable minimum resolution that is deemed useful for tactical navigation seems to be 300m (IICWG 2019), although other surveys seem to report that there could be some use for products with a resolution between 1km and 25km (Wagner 2019).

Likewise, the urgent need for higher **temporal resolution** is evident from virtually all user surveys. Especially in the marginal ice zone, ice conditions can change dramatically in a matter of hours. Therefore, sea-ice information products need to be delivered with high update frequency and timeliness. For instance, for tactical navigation, an information product is considered outdated if its valid time is more than 24 hours in the past (IICWG 2019).

Virtually all sea-ice information products that are in routine use today are based on in-situ or high-resolution satellite observations, and involve manual interpretation of the observation data by an ice analyst. Therefore, today’s sea-ice information products have limited and unequally distributed **spatial coverage**, which can be problematic for users venturing into less frequented regions (Jeuring and Knol 2019).

Because current ice information products are based solely on observations, they make no statement about the future. By the time an information product has been derived from a set of observations and is sent to the user (often several hours after the actual observation), the information is already outdated. The **temporal coverage** of current ice information products relative to the point at which they are being used is the past or - at best - the present. There is strong demand for now-casting (producing a very short-range forecast derived from observations and valid at the present moment) and short-range forecasts that cover the next 48 hours or so (IICWG 2019). There is less demand for forecasts several days to months into the future - however, it is acknowledged that users could benefit from these forecasts if suitable products were available (Hislop 2018; Jeuring and Knol 2019). These would aid e.g. with route planning, and fleet and crew planning and management (Vauraste 2018; ACCESS consortium 2012).

2.2 Ice properties

User requirements differ substantially depending on whether the user aims to avoid all ice, operate in the marginal ice zone, or in/on/under continuous sea ice cover (Wagner et al. 2020).

The first type of users who want to avoid all ice will not care about the particular properties of the ice, so their requirement would be simply a forecast of the **likelihood of encountering any ice** at a given time or time period and in a given location or region.

Users who operate in the marginal ice zone (e.g. fisheries, tourist and research cruises) will require more detailed information such as precise information on **ice concentration and thickness, ice type, the ice edge, and ice drift.**

Finally, the third type of user is highly specialized and wants to operate on, under or in continuous ice cover. These users will require information on the **ice type and age, average thickness, drift, compression** and so forth.

The distinction between these different types of users matters, because for each of these the scope to satisfy requirements with current sea-ice forecasting capabilities is quite different.

2.3 Forecast quality

Forecast quality is the correspondence between forecasts and matching observations. It should not be confused with forecast value, which is the incremental benefit realized by decision-makers through the use of forecasts (Jolliffe and Stephenson 2012). While forecast value is user-specific, forecast quality is less so. A forecast that has low quality because it consistently fails to match

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observations will have very low value to most users. Therefore, good forecast quality is indispensable for useful information products.

Detailed but easily understandable information about forecast quality needs to be made available to the user, so that they are in a position to judge whether the forecast product provides added value in their decision-making process.

2.4 Forecast presentation and communication

This concerns the design and dissemination of the actual information product. From user interaction within the SALIENSEAS project, it has become very clear that small differences in the presentation of a forecast can make the difference whether it is used or not. For instance, international **WMO standards** for ice nomenclature and ice chart color codes should be followed (WMO 2014; WMO/JCOMM 2014), and forecast products should be integrated with other ice information products already being used.

A key requirement for useful sea-ice forecasts is to make the **uncertainty estimate** an integral part of the forecast product. This has been reported numerous times (Wagner 2019). Depending on time and region, forecasts can be anything from virtually certain to completely uncertain. This information needs to be conveyed to allow the user to appropriately include the forecast product into their decision-making process.

For users that need to access information products while at sea, there are severe limitations regarding data bandwidth (e.g. reliance on Iridium link) or processing capability. Therefore, it is important to find ways to **condense complex forecast information** into formats that are small enough to be transmitted even through an Iridium connection and are easy to integrate into the workflow available on the vessel.

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3. Current forecasting capabilities

We focus here mainly on sea-ice forecasts that are operationally provided by CMEMS and C3S, augmented by forecasts for the extended (sub-seasonal) range provided by ECMWF because there are currently no extended-range forecasts provided by CMEMS or C3S.

3.1 Forecast resolution and coverage

Some general remarks

Resolution refers to the spatial or temporal distance between data points, whereas **coverage** refers to either the forecast length (forecast lead time) or the geographical area included. Information products as well as forecasting systems need to balance the two competing requirements of resolution and coverage to keep the data and computation cost manageable. Requiring both to increase at the same time is equivalent to asking for a multiple of currently available computation and data handling resources.

Affordability to compute, store and use forecast data is a major issue, because data size scales quadratically with the spatial resolution, and linearly with the area and time range covered, as well as the temporal resolution applied. Hence, forecasting systems make affordability compromises in resolution and coverage.

To illustrate, representing a single map of the Baltic Sea discretized at a 10m resolution requires about 4 billion data points, which results in at least 4 GB of data. Even taking into account savings from data compression or the conversion to vector-based formats, this is far beyond the size that users report to be able to process when at sea (IICWG 2019). This naive back-of-the-envelope computation does not even take into account that users need more than one sea-ice parameter and may need multiple time steps, which would further increase the size of the data. Moreover, any ship navigating seas that are larger than the Baltic Sea might need information products that cover a much larger area - the Baltic Sea accounts for only about 1 % of the world's sea surface that is potentially ice-covered.

In addition to affordability considerations, **spatial resolution** in physics-based forecast models is limited by the **validity of numerical representations of physical processes.** Physics-based forecast models have upper resolution limits. Beyond these limits, certain physical processes are not correctly represented anymore. Even though it is in principle possible to run the models at arbitrarily high resolutions, the results will be close to meaningless because they do not appropriately represent the physics at this spatial scale.

The most relevant limitation in the context of this report is the nature of the currently employed sea-ice models. They are based on the assumption that sea ice is a continuous medium that reacts smoothly to changes in forcing from the atmosphere above and the ocean below, with most using rheologies developed to be valid on spatial scales of 100 km or more (e.g. Hibler 1979). This might be an acceptable approximation at scales of several kilometers, but is certainly not valid at the scale of individual floes (Rabatel, Labbé, and Weiss 2015; Rampal et al. 2016; Coon et al. 2007).

Below spatial resolutions of 1 km, a completely new approach to sea-ice modelling is needed, which explicitly accounts for the discrete nature of ice floes. Promising physics-based models for this regime have existed for some time (e.g. Hopkins, 1996) but it is only recently that sufficient low-cost computational resources have become available to make their further study and development feasible (Rabatel, Labbé, and Weiss 2015; Herman, Cheng, and Shen 2019). However, these are so far only being used in idealized simulations - a plethora of research and development problems need to be overcome before operational applications are within reach.

Current operational forecasts

Current-generation numerical forecasting systems are able to provide regional or global forecasts of basic sea-ice parameters with a spatial resolution of up to 3 km, with up to hourly temporal resolution, and an update frequency of up to several times a day. The systems broadly fall into three categories according to how far into the future the forecasts are valid (called the lead time): **short- and medium-range (SMR) forecasts** have a lead time of up to two weeks. They usually feature higher resolution and are updated at least once a day. **Extended-range or subseasonal (ER) forecasts** try to predict sub-seasonal anomalies occurring a few weeks ahead, are usually updated every few days, and provide coarser resolution. Even longer ahead, **long-range or seasonal (LR) forecasts** aim at giving guidance on seasonal anomalies up to a year ahead. Because of computational constraints, they provide even coarser resolution and are usually only updated once a month.

CMEMS is currently providing several short-to-medium-range (SMR) forecasts (see Table below and KEPLER report D2.2). C3S is providing a multi-model seasonal (LR) forecast. However, extended-range (ER) forecasts are not provided by either CMEMS or C3S.

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Forecasting system	Provider (producer)	Forecast range	Compo-nents	Spatial coverage	Update frequency	Spatial resolution
Seasonal multi-system	C3S (several)	6 months (LR)	IOA	global	monthly	1°[1]
ENS-extended	ECMWF	7 weeks (ER)	IOA	global	twice-weekly	36 km
GLO-CPL	CMEMS (UKMO)	10 days (SMR)	IOA	global	daily	1/4°
GLO-HR	CMEMS (MERCATOR)	10 days (SMR)	IO	global	daily	1/12°
ARC-MFC TOPAZ	CMEMS (METNO)	10 days (SMR)	IO	Arctic	daily	12.5 km
ARC-MFC neXtSIM-F	CMEMS (NERSC)	7 days (SMR)	I	Arctic	daily	3 km
BAL-MFC	CMEMS (DMI/BSH)	6 days (SMR)	IO	Baltic	twice-daily	2 km

Table 1: Sea-ice forecasting systems available through CMEMS, C3S and ECMWF. The forecast range abbreviations are LR = long-range (seasonal), ER = extended-range (sub-seasonal), SMR = short-to-medium range. Model component abbreviations: I = sea ice, O = liquid ocean, A = atmosphere.

3.2 Forecast ice properties

Physics-based forecast models in use today are able to provide at least the following basic sea-ice properties: **sea ice concentration (SIC)**, **sea-ice thickness (SIT)**, **sea-ice drift (SIU and SIV)**, and **thickness of snow on sea ice (SNOW)**. These properties are provided as grid-cell means, i.e. are spatial means over areas of the size of the spatial resolution. Depending on the forecasting system, not all of these are distributed to the user (see Table 2).

Some forecast models may provide additional properties like area fraction and thickness for different sea-ice **thickness categories** within the grid cell, **ice age**, or thickness and area fraction of **rafted and ridged ice** (Lensu and Goerlandt 2019). Although the often-required parameters **ice type**

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[1] higher resolution available depending on underlying forecasting system (up to 36km)

and **ice pressure** are not directly available from the models, it is possible to derive proxies for them from the available model parameters.

Below is a table listing which sea-ice parameters are *disseminated* for each of the operational forecasting systems mentioned before. Note that there are usually many more sea-ice parameters available from the forecast model, but for various reasons it was decided not to disseminate them. Therefore, in many cases it is straightforward to extend the list of *disseminated* parameters should this be deemed appropriate. For instance, there is ongoing work in C3S to make sea-ice thickness available.

Forecasting system	***Sea-ice parameters***
Seasonal MS	*SIC*
ENS-extended	*SIC, SIT, SIU, SIV, SNOW*
GLO-CPL	*SIC, SIT, SIU, SIV*
GLO-HR	*SIC, SIT, SIU, SIV*
ARC-MFC (TOPAZ)	*SIC, SIT, SIU, SIV, SNOW, SIALB, SIAGE*
ARC-MFC (neXtSIM-F)	*SIC, SIT, SIU, SIV, SNOW*
BAL-MFC	*SIC, SIT*

Table 2: Sea-ice properties provided by forecasts from CMEMS, C3S and ECMWF. SIC = sea-ice concentration, SIT = sea-ice thickness, SIU + SIV = sea-ice drift, SNOW = thickness of snow on sea ice, SIALB = sea-ice albedo, SIAGE = sea-ice age. See appendix for a combined view of Tables 1 and 2.

3.3 Forecast quality

General remarks

Forecast quality varies drastically - from virtually perfect to completely useless - **depending on the target of the forecast**:

- geographical region and time of the year
- forecast lead time, i.e. how far ahead into the future the forecast goes
- spatial and temporal resolution
- sea-ice property of interest

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Additionally, forecast quality for the same target can vary equally dramatically between **forecasting systems**, depending on many factors:

- appropriateness of resolution and coverage
- fidelity of numerical representation of physical processes in the forecast model
- quality and completeness of forecast initialization
- representation of forecast uncertainty

It is important to note that making statements on the quality of a forecasting system is only possible in a **statistical sense**. Each forecast case is unique, and the forecast error can vary widely between different cases. Therefore, the forecast for each **individual case** must be used together with robust statistical information about the expected quality derived from many past forecasts that have been verified against the observed outcome.

Availability of past forecasts and ensembles for quality assessment

An important user requirement is the availability of an **uncertainty estimate.** This can only be provided reliably if the forecasting system meets two important requirements:

1. Provision of a **large archive of previous forecasts**, with a configuration that is as similar as possible to the real-time forecast for which the user requires an uncertainty estimate. Ideally, retrospective forecasts are performed whenever updating a forecasting system. However, if changes in the forecasting system are minor, it might be sufficient to provide as many previous real-time forecasts as possible, even if they had been made with a previous and slightly different version of the forecasting system.
2. Provision of a measure of case-dependent intrinsic forecast uncertainty with each forecast. This requires **ensemble forecasts**, i.e. computing several equally likely outcomes of the same forecast.

The first requirement is indispensable for **forecast calibration** and **skill assessment**. Forecast calibration is the process of correcting known forecast deficiency such as biases a posteriori, based on a large sample of forecasts that can be verified against observations. Forecast calibration allows to extract the maximum amount of information and potential value of a forecast by correcting for known deficiencies as much as possible (see Dirkson, Denis, and Merryfield (2019) for an explicit and instructive example). Likewise, a large archive of previous forecasts is necessary to robustly establish the **forecast skill**, i.e. the average error that the forecasting system should be expected to make for a specific target. It is important to note that skill is an average property of a forecast, and variations in forecast errors should be expected for each individual forecast case.

This leads to the second requirement, the provision of **ensemble forecasts** as an objective measure of forecast uncertainty to be expected in the specific case at hand. Ensembles give a direct measure

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of forecast uncertainty than the average properties of past forecasts, and are an indispensable prerequisite for **reliable forecasts** (see Palmer (2020) for more discussion on that).

It needs to be appreciated that the requirement of providing a large archive of previous forecasts as well as ensembles adds significantly to the data and computation cost of forecasts discussed previously. In order to allow statistically significant conclusions from a data set of previous forecasts, a reasonable size for a sample of comparable forecasts might be 100. A reasonable lower limit for ensemble size might be 10 realizations, with 100 members or more needed to sample rare events. **The requirement to provide past forecasts and forecast ensembles easily leads to a 1000-fold increase in data and computing costs and competes with the requirements of increased spatial and temporal resolution.**

For these and other reasons, only some of the current operational forecasting systems that disseminate sea-ice parameters fulfil the above-mentioned requirements and disseminate ample re-forecast and ensemble data:

Forecasting system	**ensembles**	**re-forecasts**	**forecast archive**
Seasonal MS	yes	1993-2016	since 2017
ENS-extended	yes	last 20 years	yes
GLO-CPL	no	no	since 1/2016
GLO-HR	no	no	since 1/2016
ARC-MFC (TOPAZ)	no[2]	no	since 1/2016
ARC-MFC (neXtSIM-F)	no	no	since 11/2018
BAL-MFC	no	no	since 3/2016

Table 3: Forecast ensembles and past forecasts provided by sea-ice forecasting systems from CMEMS, C3S and ECMWF. Re-forecasts are also called retrospective forecasts or hindcasts - they are expressly produced with a fixed forecasting system to allow calibration and skill assessment of real-time forecasts. “Forecast archive” denotes past real-time forecasts that have been produced with a potentially changing forecasting system. See appendix for a combined view of Tables 1-3.

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[2] A 10-members ensemble forecast is computed but not made available through the CMEMS portal.

Currently available quality assessments

There is ample research on the quality of numerical forecasts for large-scale sea-ice presence. This research is looking for potentially useful correspondence between the forecasts and observations. An often-used approach to judge the potential usefulness of a numerical forecast is to compare its biases and errors to that of a trivial reference forecast which can be easily derived from the statistics of past observations and requires hardly any computing resources to produce. A forecast is deemed skillful if it has a higher quality than the reference forecast. A consistent finding across this research is that currently operational physics-based forecast models provide **skillful forecasts of the large-scale sea-ice presence for some regions and seasons**. In the following, we will provide a few examples of this quality assessment research for numerical sea-ice forecasts over the last 10 years.

A number of studies suggest that large-scale (**ocean-basin scale**) sea-ice anomalies in the Arctic are potentially predictable months or even years ahead (Koenigk and Mikolajewicz 2008; Blanchard-Wrigglesworth et al. 2011; Tietsche et al. 2014). However, these studies often focus on targets like the pan-Arctic sea-ice volume or extent, which is of little relevance for most operational users. For more user-relevant targets, like the seasonal time of opening of the Northern Sea Route, the potential predictability is often much lower (Melia et al. 2017). A second major obstacle in translating these idealized research results into usable forecasts is the prevalence of model error, which is important especially at longer time scales when forecasting months to years ahead, and which is usually ignored in these idealized studies.

When assessing more realistic forecasts, which are initialized from and try to predict observations, the achievable forecast skill is usually much lower. Nevertheless, it is routinely found that current numerical prediction models can skillfully predict large-scale sea ice anomalies in the Arctic **a few months ahead**. For instance, (Dirkson, Denis, and Merryfield 2019) report that the C3S multi-model seasonal forecast for Arctic sea-ice cover during the annual minimum in September is substantially better than simple statistical forecasts derived from past observations. This is, however, only achieved after careful calibration of the forecasts. From Figure 2 it can be seen that even forecasts initialized 6 months ahead (in April) display significant skill for parts of the Northern Sea Route. Forecast skill becomes higher the shorter the lead time until September - a forecast issued by the C3S multi-model at the beginning of August should be expected to be able to predict September sea-ice concentration better than a statistical reference forecast throughout the Arctic Ocean domain.

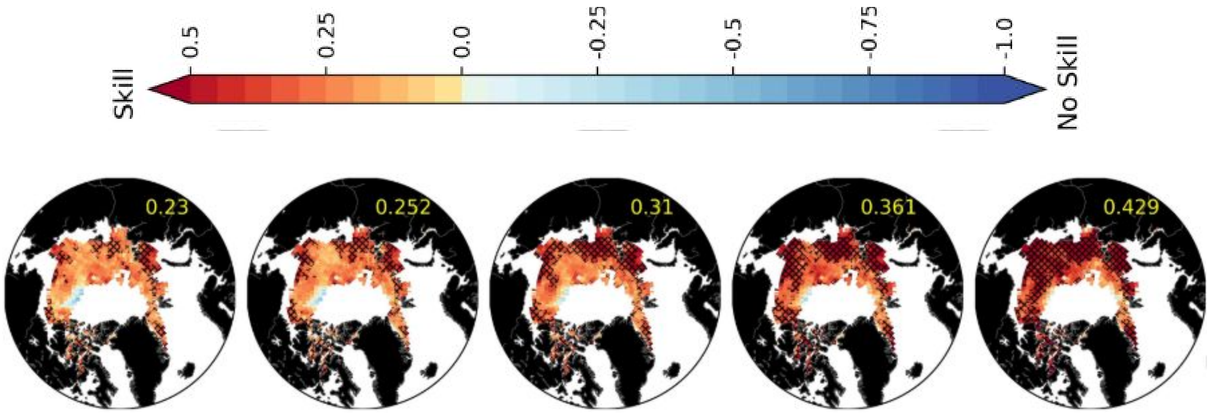

Figure 2: Maps of CRPSS (continuous rank probability skill scores) for September sea-ice concentration initialized from (from left to right) April, May, June, July and August for the C3S multi-model ensemble relative to trend-adjusted climatology. Spatial-mean CRPSS values are displayed in the upper right of each map. Hatching indicates where CRPSS > 0 at the 90% confidence level, i.e. the numerical forecast is better than a simple statistical reference forecast from past observations. Figure reproduced from (Dirkson, Denis, and Merryfield 2019).

For **sub-seasonal time scales** (weeks ahead), forecast skill for current numerical prediction systems extends to smaller scales of **10-100 km** (Zampieri, Goessling, and Jung 2018). The skill is highly dependent on the region and season though. Moreover, verification of sea-ice forecasts at these higher spatial resolutions and with higher accuracy requirements is problematic, as the passive microwave observations of sea-ice concentration that are widely used in the climate and forecast research community are not appropriate anymore, and new approaches are needed.

We present here an example of sea-ice forecasts for the Baltic Sea, which grew out of a KEPLER-inspired collaboration between a forecast provider (ECMWF) and an ice service (FMI). The skill of retrospective sea-ice concentration forecasts for the Baltic sea, which are used for skill assessment and calibration of the operational ECMWF extended-range with cycle 46r1, has been verified using sea-ice concentration from digitized ice charts produced jointly by FMI and SMHI, and made available through the CMEMS products portal. This can inform the dialogue between forecast producers and users on if and how these forecasts can be turned into information products relevant for marine users.

Figure 3 concerns itself with forecasts of weekly-mean sea-ice concentration three weeks into the future and makes two points: first, the forecasts consistently underestimate sea-ice concentration along the coasts, especially in the Gulf of Bothnia and around the Aland Islands. For marine users, knowledge of sea-ice cover is most critical close to coasts, so this bias presents a major usability challenge. The second point, however, is that away from the coasts there are sizable areas with at least a moderate amount of forecast skill in the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga. In these regions (but not elsewhere), these forecasts can potentially add value over using a simple forecast based on past observations.

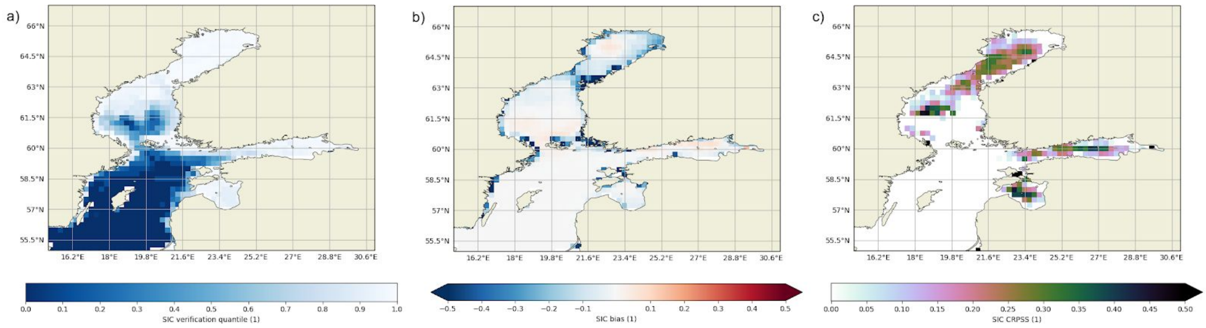

Figure 3: Skill of ECMWF forecast of sea-ice cover three weeks ahead when verified against digitized ice charts obtained from CMEMS. The figure is based on 56 ensemble forecasts with 11 members in Jan/Feb/Mar 2012-2019 with the currently operational IFS version 46R1. Panel (a) shows the maximum sea-ice concentration present at any time in the ice charts. Panel (b) shows the forecast bias in sea-ice concentration, i.e. where the forecast consistently over- or underestimates sea-ice concentration. Panel (c) shows the Continuous Ranked Probability Skill Score (CRPSS), which compares the IFS forecast against an empirical forecast based only on past observations. In areas where CRPSS > 0, the IFS forecast has more skill than the empirical forecast and therefore can potentially provide added value. A perfect forecast would have CRPSS = 1. Note that negative CRPSS values (where the IFS forecast performs worse than a simple empirical forecast) are masked white.

On **weather time scales** (days ahead), there are some efforts to routinely monitor forecast performance of some of the CMEMS forecasts. A continuously updated assessment of ARC-MFC forecast performance available under https://cmems.met.no/ARC-MFC/V2Validation/index.html, with the metrics and methods employed documented in Melsom, Palerme, and Müller (2019). An important insight from this work is that finding user-relevant metrics for forecast verification is not straightforward and requires careful design that takes into account known user requirements or, ideally, actively involves the users themselves.

Melsom, Palerme, and Müller (2019) also demonstrate explicitly and objectively how forecast skill decreases for increased spatial resolutions: Figure 4 illustrates that the ARC-MFC forecasts of the ice edge 5 days ahead have substantial skill at spatial scales above 10km, but have vanishing skill on spatial scales of 1 km, which is the resolution the ice charts are provided on.

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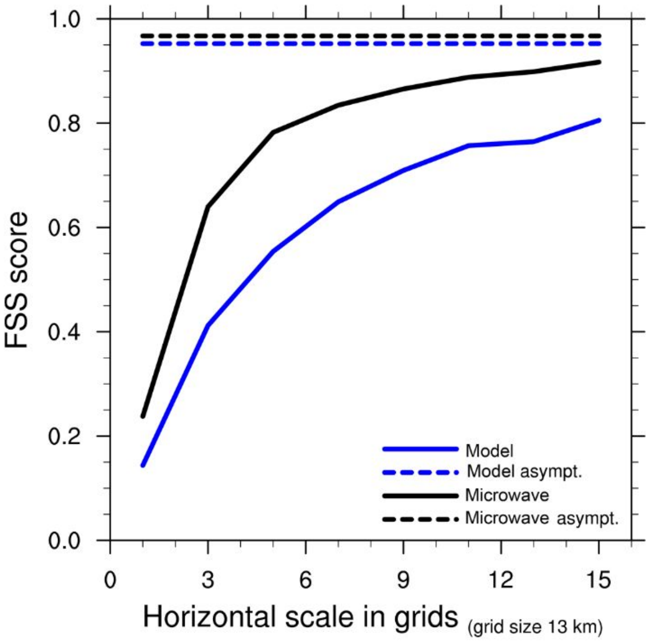

Figure 4: Forecast skill (Fractional Skill Score, FSS) for the ice edge as a function of resolution for ARC-MFC (TOPAZ) forecasts 5 days ahead versus ice chart data (blue line) and microwave data vs. ice chart data (black line). Dashed lines show asymptotic FSS values. Results are based on forecast bulletins and microwave data from January 2017 to mid-May 2017. Figure reproduced from Melsom, Palerme, and Müller (2019).

3.4 Forecast presentation and communication

Although there are few examples where raw sea-ice forecasts are turned into mature, operationally and freely provided information products with a high relevance to end-users, there are many examples of research activities and pilot studies aiming to develop these information products, with varying degrees of maturity. Here, we present two concrete examples where attempts have been made to derive more user-relevant information products from currently available numerical forecasts. The first example concerns longer lead times weeks or months ahead that could be relevant for planning. The second example concerns shorter lead times of only a few days ahead, and demonstrates that numerical sea-ice drift forecasts are already being actively used by the MOSAiC expedition.

Pan-Arctic maps of IMO Polar Code Risk Index Outcome from ECMWF extended-range forecasts

In 2017, FMI produced a product demonstrator to help plan an ice breaker transit from Korea to Finland in July 2017. The product demonstrator was based on sea-ice concentration and thickness from the ECMWF extended-range forecast initialized on 1 June 2017, together with hindcasts for calibration. A simple approximation of the IMO Risk Index Outcome (RIO, (IMO 2016)) was computed from the forecast model's sea-ice concentration and thickness field.

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Figure 5 shows a map of the Arctic with shades of green, yellow and red overlaid. This is based on ECMWF extended-range forecast fields from 50 ensemble members with a lead time of 30 days. Regions where the RIO approximation is greater than 0 (“normal operations”, simplified as “go”), the map is coloured green, for -10 < RIO < 0 (“elevated operational risk”, simplified as “go slowly”) the map is coloured yellow, and for RIO < -10 (“operation subject to special consideration”, simplified as “no go”) the map is coloured red. The innovative aspect of this product demonstrator is the depiction of forecast uncertainty by changing the saturation of the three colours depending on the forecast uncertainty measured by the ensemble spread. If the ensemble spread is low, uncertainty should be expected to be low, and the colour is shown fully saturated. The saturation of the colour is reduced where ensemble spread is elevated and indicates higher forecast uncertainty. This “fog of uncertainty” might be a visual depiction of forecast uncertainty that can be intuitively interpreted correctly by the user.

Based on these product demonstrators, the icebreaker transit was through the Northwest Passage on 5 – 29 July, not along the Northern Sea Route, and it set a record for the earliest passage of the Arctic within a summer season.

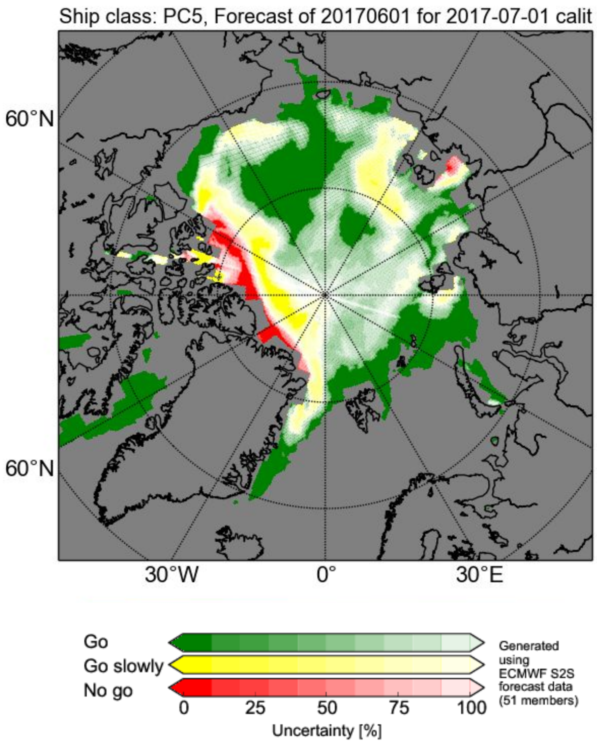

Figure 5: Product demonstrator for an extended-range forecast of IMO Risk Index Outcome for a Polar Class 5 ship. The map is computed from the ECMWF extended-range forecast from 1 July 2017

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with a lead time of 30 days. Credit and all rights to this figure lie with J. Haapala, A. Gierisch and P. Uotila (Finnish Meteorological Institute).

Consensus drift forecast for the MOSAiC expedition

Within the **Sea Ice Drift Forecast Experiment** (AWI n.d.), sea-ice drift forecasts for a number of buoys drifting in the Arctic Ocean have been collected from about a dozen international operational forecast centres and research groups, largely in (near-)real-time, since 2017. In particular, these forecasts have successfully been used to construct real-time consensus forecasts for the MOSAiC 2019-2020 drift campaign for lead times up to 120 days, with explicit quantification of forecast uncertainty based on the multi-system ensemble. The forecasts have been provided as three different product variants (Figure 6) to meet user requirements, in particular for the advance-ordering of high-resolution (SAR) satellite imagery. According to a qualitative assessment by the person in charge, the hit rate (drift camp contained in the SAR images) has increased to about 90% from about 50% during earlier campaigns when no comparable forecasts were available. SIDFEx may serve as an example for new sea-ice forecast products derived from existing operational forecast systems that have incorporated dynamical sea-ice components over the course of the past decade. Possible future applications may include oil-spill response and the search-and-rescue sector.

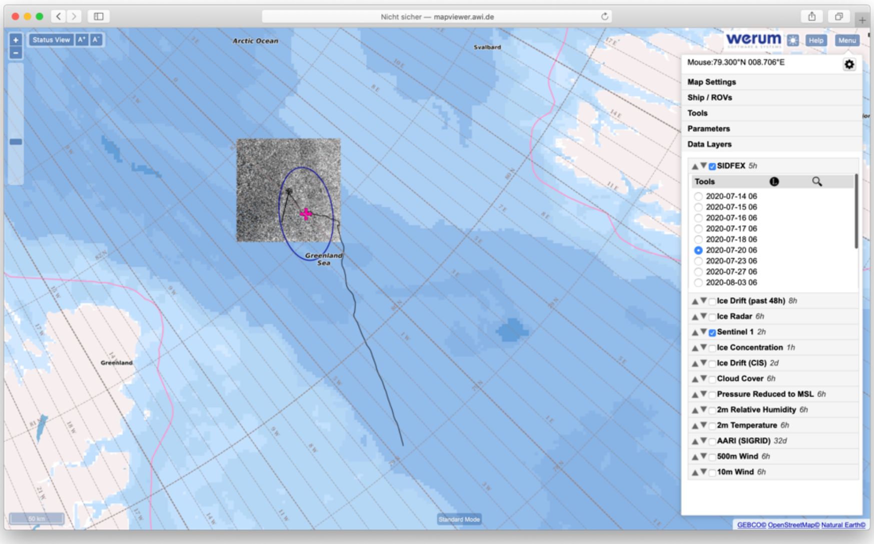

Fig. 6: SIDFEx consensus forecast for the drift of the MOSAiC campaign, issued July 13th 2020 at 06:00 UTC, as displayed in the onboard mapping system of RV Polarstern. For the selected lead time (here July 20th), a pink cross and a blue ellipse denote the most likely position and the 90% confidence bound. The most recent Sentinel-1 SAR image is also shown; various other products can be overlaid (see the legend on the right). The same SIDFEx forecasts are also provided as a standing-alone graphical product

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(https://swiftbrowser.dkrz.de/public/dkrz_0262ea1f00e34439850f3f1d71817205/SIDFEx_Graphical/) and through an interactive web tool (https://sidfex.polarprediction.net).

4. Gap analysis: user requirements versus current capabilities

4.1 Forecast resolution and coverage

Spatial resolution is the most important gap between user requirements and current capabilities. For tactical decisions, the currently possible spatial resolutions of sea-ice forecasts of 5km or more are simply not appropriate, at least not if they only provide grid-cell mean sea-ice properties. Many user surveys have shown that sub-kilometer resolution is required.

Spatial coverage of numerical sea-ice forecasts is usually not a problem, because they tend to be either global, or cover an entire ocean basin or an enclosed sea.

The **temporal resolution** currently provided by sea-ice forecasts from CMEMS and C3S is daily or hourly, which seems to be sufficient for most of the reported user needs. However, there is a lack of documentation on the quality of forecasts to represent sub-daily variability of the ice, and due to their nature it is to be expected that currently used sea-ice models are not well suited to simulate fast sea-ice processes that constitute rapid changes of local conditions within a few hours. To verify forecasts on sub-daily time scales, appropriate observations with sub-daily temporal resolution are required. These are currently not provided.

The **temporal coverage** of sea-ice forecasts available from CMEMS spans the short-to-medium range, which could support planning decisions pertaining operations a few days ahead. C3S delivers seasonal forecasts, which could provide an indication whether the coming season brings unusual conditions. However, neither CMEMS nor C3S delivers extended-range forecasts, which could provide support decisions with a lead time of a few weeks, e.g. for route planning.

The **update frequency** (weekly to daily) of sea-ice forecasts (currently daily for the short-range CMEMS forecasts) is maybe too low for the sea-ice forecast system to ingest the most recent observations. The strong requirements on observation latency for the relevant satellite missions (including the HPCMs) should trigger the development of forecasting systems towards shorter update cycles and data assimilation of Level-2 sea-ice products (instead of daily analysed Level-3 or Level-4 products as is the case today).

4.2 Forecast Ice properties

Current forecasting systems provide basic sea-ice properties such as sea-ice concentration, thickness and drift. These are relevant to users who want to avoid all ice as well as some users that operate in the marginal ice zone.

However, users who operate on, under or in continuous ice cover need information about many additional sea-ice properties, such as ice type, compression, presence of ridges or leads, etc. These **advanced sea-ice properties are not served** by current forecasting systems.

It might be possible to provide useful information on some of these currently missing sea-ice properties by means of employing physical parameterizations of the relevant processes. Current sea-ice models have, for instance, the ability to forecast the statistical distribution of floe sizes, lead density, or the area fraction of ridged ice. However, there is a lack of understanding how well these properties modelled via a subgrid-scale parameterization perform against observations, and there is a lack of these observations in adequate spatial and temporal resolution.

4.3 Forecast quality

Although there are strong efforts in Copernicus for stringent product validation (see KEPLER report D2.2), much more work is needed to establish the quality of sea-ice forecasts when verified against specific user-oriented targets. Melsom, Palerme, and Müller (2019) discuss a range of potentially user-relevant metrics when verifying short-to-medium-range sea-ice forecasts from the ARC-MFC TOPAZ system served by CMEMS. However, similar assessments need to be available for each forecasting system, with standardized metrics that allow the user to easily compare forecast quality between different systems.

This lack of forecast quality documentation has multiple potential underlying causes, which each need to be addressed:

1. The forecasts are not always provided together with an archive of past forecasts and forecast ensembles. This makes the assessment of forecast quality difficult (see Section 3.3).
2. User-relevant sea-ice observations are not readily available with spatial and temporal coverage and in data formats suitable for forecast verification. For instance, gridded ice charts for the Arctic provided by CMEMS currently cover only the Baffin Bay, Greenland Sea, Fram Strait and Barents Sea, and are available only from 2018 onwards. Other satellite-derived products have issues especially along the coast and at higher resolutions.
3. There might be a lack of communication between the institutes who provide the forecasts on the one hand, and the intermediate or end-users on the other hand, or a lack of funding or interest in either of these parties. A user-relevant assessment of forecast quality relies on a sustained dialogue between both parties.

It is also possible that for the resolution and coverage most relevant for the end-users, currently operational sea-ice forecasts simply lack the quality to make them useful. However, this would be an important insight that needs documentation created collaboratively by forecast producers and users. As it stands, a currently **poor understanding of forecast quality is blocking progress with user uptake**.

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4.4 Forecast presentation and communication

There is a **lack of explicit “expectation management”** of what the forecast can provide for any specific forecast target. A formal uncertainty estimate that is computed for the concrete target at hand is not provided by any sea-ice forecasting system in C3S and CMEMS. The provision of uncertainty estimates is not an easy task, for the same reasons listed above why assessments of forecast quality might currently be lacking.

It needs to be explicitly acknowledged that **forecast uncertainty varies strongly** with all forecast parameters: lead time, spatial scale, sea-ice property, region, season, etc. Moreover, forecast uncertainty varies strongly for each forecast case - this can only be quantified by using forecast ensembles. Currently, no explicit forecast ensembles are available from CMEMS.

Another important aspect of forecast communication that is not well handled is the following: users experience **forecast cases**, but forecast providers document **average forecast properties**. The relationship between the two is not trivial, but can be documented and communicated. A forecast can only be considered bad for a particular case if its error is clearly higher than what should be expected from (i) past (average) performance established through the assessment of past forecasts and (ii) the uncertainty suggested by the spread of the forecast ensemble.

In closing, it should be said there seems to be a two-way lack of understanding: **users might lack training in what forecasts can and cannot provide, and producers might be unaware of specific user requirements.**

4.5 Closing remark on gap analysis

For **tactical navigation**, users need to know about the sea ice now, i.e. they require an information product valid for today, ideally with sub-daily updates. They require precise decameter-scale resolution and detailed sea-ice properties. The first requirement is impossible to meet with today’s numerical sea-ice forecast models, both because they are fundamentally not appropriate for the spatial scales required, and because the computational cost to model a domain larger than a few kilometers would be prohibitive. However, simulating statistics of small-scale sea ice properties within a large (a few kilometers) domain are already possible in principle, but there is a lack of dedicated research and development.

For forecasts **days to months ahead**, today’s numerical sea-ice forecasts might provide enormous untapped potential, but there are severe risks of misinterpreting the forecasts and deriving misleading information products from them. So far, only a few experimental research and pilot studies exist that try to create useful information products from the raw model output. Forecast quality assessments and forecast information products need to be co-developed by forecast producers and users.

5. Recommendations for improving user-relevance of sea-ice forecasts

We group our recommendations into several streams of research and development work that can be addressed with relative independence and at different speeds. The time frame for which results can be expected varies considerably. Some improvements (e.g. better forecast communication) should be easily attainable in the near future with a little bit of effort and additional funding, whereas other improvements (e.g. new class of physics-based sea-ice forecast models) still require basic research and have many developmental milestones ahead of them before being potentially usable for user-relevant forecasting.

Stream 1: Improved understanding and utilization of existing forecasts

This stream of work can be carried out by the core Copernicus Services with the aid of the forecast producers and end-users. Improvements should be easily obtained in the short- to medium term by better exploiting synergies of expertise and tools that already exist across the different stakeholders of sea-ice forecasts.

Copernicus should further foster the **collaboration between forecast producers, intermediate users and end-users** (see KEPLER report D1.4), in order to build a mutual understanding of requirements and constraints and develop more useful representation and communication of sea-ice forecasts. **Training activities** for intermediate and end-users on how to use and interpret the forecasts are an important tool to do that.

Skill and uncertainty of already provided parameters (e.g. SIC, SIT, drift) against relevant targets (e.g. ice charts) needs to be **assessed more systematically and be provided as part of the forecast.** The provision of forecast uncertainty is essential for the user to make more informed decisions on whether a particular forecast provides any added value for a particular decision that needs to be made. Developing useful and reliable sea-ice forecast products requires **sustained interaction between forecast users and producers** to scope potentially useful products and then co-develop them.

It should be investigated which **additional sea-ice parameters** that are required but currently not provided could be easily provided with some confidence, without further evolution of the forecasting systems.

Stream 2: Evolution of existing forecasting systems

This stream of work will mainly be carried out by the forecast producers. The role of the Copernicus Services would be to (i) provide the technical framework to allow the provision of ever larger and more complex data sets and (ii) stimulate and support research and development of user-relevant *improvements to the forecasting systems. Progress will be gradual and continuous over the short to long term.*

The **use of sea-ice observations for forecast initialization** needs to be improved, e.g. the necessary research needs to be conducted to assimilate Level-2 (orbit-based) sea-ice products instead of Level-3 and Level-4 as is the case today (see D3.3). This is especially relevant to the Copernicus HPCMs.

The **spatial resolution** of current sea-ice forecasts should be increased as far as possible. Since sea ice, the atmosphere and the liquid ocean are strongly interdependent, any resolution increase in the sea-ice component needs to be accompanied by resolution increases in the atmosphere and the ocean. It is important to acknowledge that current sea-ice models are fundamentally not appropriate for modelling sea ice at scales below a few kilometers, so the potential for resolution increases is limited.

It is essential to further **reduce forecast biases** in the coupled atmosphere-ocean-sea-ice forecast system. These are often limiting the usefulness of current sea-ice forecasts. At longer lead times, most bias improvements might come from improving the model quality, while at shorter lead times, improvements in data assimilations methodology might be most promising.

There are many potential **improvements to data assimilation schemes** (see also KEPLER report D2.2). Depending on the focus of the system, these might include more rapid update cycles in combination with using observations at lower data levels (Level 2 or even Level 1, see also ECMWF (2018), which in turn require much more sophisticated observation operators to map the observations to the model equivalent.

The widespread provision of **ensembles** and **retrospective forecasts** is essential to calibrate forecasts and robustly assess their skill. Having a large archive of forecasts is also essential as training data for machine-learning approaches.

Attempts should be made to close the spatial resolution gap by providing **probabilistic information about decameter-scale features on a coarser grid** (e.g. lead or ridge density in a given area of 10 x 10 km). This can be done from forecast ensemble information, or from subgrid-scale parameterizations. Research into the skill and usefulness of these potential products is needed.

More user-relevant sea-ice properties can be provided by constructing **proxies** from available model parameters, for instance ice convergence as a proxy for difficult ice conditions where a ship could expect to become beset. It should also be investigated how far **improved or new physical parameterizations** are able to provide some of these parameters; some examples would be a floe-size distribution, an ice-thickness distribution, or providing an area fraction of ridged ice.

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Stream 3: Improve provision of observations to allow robust forecast assessment and calibration

This stream of work on improving the provision of freely available earth observations is at the very heart of the Copernicus Services. A better provision of already existing observations can be achieved over the short term with well-manageable additional resources. New types of in situ and satellite observations, e.g. the Copernicus HPCMs, can be integrated into the Copernicus Services as and when they become available.

The availability of relevant sea-ice observations needs to be improved, in order to facilitate forecast evaluation and calibration. These observational data sets should be made available **for as many years into the past as possible**, and **in a format that can be easily used by the numerical modelling community**. For instance, gridded ice charts with larger spatial (pan-Arctic) coverage and improved temporal coverage should be provided to facilitate forecast verification.

For **advanced sea-ice parameters** (e.g. floe size distribution), it is often difficult to obtain high-quality large-scale observations to verify the model. Likewise, lack of suitable observations also prevents forecast models from initializing these parameters.

Satellite observations at **sub-daily temporal resolution** should be made available to allow the verification of sea-ice forecasts in representing sub-daily time scales.

Observational data from the Copernicus HPCM will improve the situation with important large-scale sea-ice observations relevant for forecast verification and initialization, e.g. sea-ice thickness. They should be exploited to the maximum extent possible.

Stream 4: Nowcasting and short-range forecasting using sub-kilometer scale sea-ice observations

This stream of work should be carried out by intermediate users of the Copernicus Core Services who develop downstream applications. The landscape of these intermediate users will likely be diverse and may comprise commercial entities, national weather services, and publicly funded research groups. Activities in this stream are expected to be diverse as well - they will be initiated by and focused on specific user needs and can take place at any point in time.

Hybrid forecasting methods are a promising approach to achieve sub-kilometer resolutions for short-range forecasts (Rabenstein and Kountouris 2018). This class of methods combines the ice properties derived from high-resolution satellite observations like SAR with the predicted ice drift derived from lower resolution model fields. By construction, these methods would achieve the same resolution as the observational data employed. However, this approach is dependent on further improvements to the lower resolution model fields, which currently might not have sufficient quality.

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The use of **machine learning** tools should also be considered for calibrating or downscaling low-resolution forecasts at short lead times, or for filling in observational gaps in a short-range forecast (e.g. Kountouris, Palerme, and Rabenstein 2020)

Stream 5: Develop new class of physics-based sea-ice forecast models

This stream of work is most likely still the remit of basic research, and is hence reliant on the availability of sufficient and sustained public funding. Research groups at universities, weather and climate modelling centres, and possible commercial actors are expected to participate. Considerable resources over the long term will be required to make progress with this stream of work, and the chances of the efforts eventually leading to user-relevant operational forecasting systems are still uncertain. Copernicus Services can play a role to guide this research and will provide the lower-resolution boundary conditions that these models will rely on.

For an explicit and realistic simulation of sea-ice physics with sub-kilometer resolution, a new class of sea-ice models needs to be developed. Prototypes for such models exist, but they are currently only used for basic research in an idealized context (Blockley et al. 2020). Long-term research with substantial resources and uncertain outcomes is needed to establish if and how these models can be used for operational forecasting. Some obvious questions that need to be addressed are

- Is it possible to construct a model that can simulate both the dynamics of an assembly of discrete ice floes and the dynamics of the consolidated ice pack?
- Due to the high spatial resolution, it will only be feasible to run these models over a limited spatial domain. Therefore, they will rely heavily on high-quality (but lower-resolution) boundary conditions provided by models that are more akin to current numerical forecast models.
- How will these models be initialized? Data assimilation methods need to be developed to cope with the relevant high-resolution sea-ice observations and the fact that the structure of these models differs fundamentally from current numerical forecast models, for which mature data assimilation methods exist.
- How predictable are sea-ice dynamics at the floe scale in principle? It might be that the inherent predictability of the small-scale sea-ice dynamics is very limited.

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Appendix

Forecasting system	Provider (producer)	Forecast range	Model components	Update frequency	Temporal resolution	Spatial coverage	Spatial resolution	Sea-ice parameters	ensemble	re-forecasts	forecast archive
Seasonal MS	C3S (several)	6 months (LR)	atmosphere, ocean, sea ice	monthly	daily	global	1°	SIC	yes	1993-2016	since 2017
ENS-extended	ECMWF	7 weeks (ER)	atmosphere, ocean, sea ice	twice-weekly	6-hourly	global	36 km	SIC, SIT, SIU, SIV, SNOW	yes	last 20 years	yes
GLO-CPL	CMEMS (UKMO)	10 days (SMR)	ocean and sea ice	daily	hourly	global	1/4 °	SIC, SIT, SIU, SIV	no	no	since 1/2016
GLO-HR	CMEMS (MERCATOR)	10 days (SMR)	ocean and sea ice	daily	hourly	global	1/12 °	SIC, SIT, SIU, SIV	no	no	since 1/2016
ARC-MFC (TOPAZ)	CMEMS (METNO)	10 days (SMR)	ocean and sea ice	daily	hourly	Arctic and North Atlantic	12.5 km	SIC, SIT, SIU, SIV, SNOW, SIALB, SIAGE	no	no	since 1/2016
ARC-MFC (neXtSIM-F)	CMEMS (NERSC)	7 days (SMR)	sea ice	daily	hourly	Arctic and North Atlantic	3 km	SIC, SIT, SIU, SIV, SNOW	no	no	since 11/2018
BAL-MFC	CMEMS (DMI/BSH)	6 days (SMR)	ocean and sea ice	twice-daily	hourly	Baltic Sea	2 km	SIC, SIT	no	no	since 3/2016

Table 4: Overview of sea-ice forecasts available from CMEMS, C3S and ECMWF (combined view of Tables 1-3)

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