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Earth system assimilation for the cryosphere: Status and way forward [TD-01]

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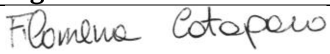
ESA	Filomena Catapano		21 Jul 2025
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Abbreviations

3D-Var .... Three-dimensional variational
4D-Var .... Four-dimensional variational
AD........................ Adjoint
ADF .... Auxiliary data files
AltiKa................... Altimeter in Ka-band
AMSR2 .... Advanced Microwave Scanning Radiometer 2
AMSR-E .... Advanced Microwave Scanning Radiometer for EOS
APPLICATE........ Advanced Prediction in Polar Regions and Beyond: Modelling, Observing System Design and Linkages associated with a Changing Arctic Climate
ATBD................... Algorithm Theoretical Basis Document
CCI....................... Climate Change Initiative
CEM-PAL............ Copernicus Expansion Mission Product Algorithm Laboratory
CERA-SAT.......... Coupled ECMWF Reanalysis for the Satellite Era
CICE .... Los Alamos Sea Ice Model
CIMR .... Copernicus Imaging Microwave Radiometer
CRISTAL............. Copernicus Polar Ice and Snow Topography Altimeter
CS2SMOS............ CryoSat-2–SMOS
DA........................ Data assimilation
DANTEX............. Data Assimilation and Numerical Testing for Copernicus Expansion Missions
ECMWF............... European Centre for Medium-Range Weather Forecasts
EDA .... Ensemble of Data Assimilations
EM .... Electromagnetic
ESA...................... European Space Agency
EUMETSAT .... European Organisation for the Exploitation of Meteorological Satellites
FGAT .... First guess at appropriate time
ICESat-2.............. Ice, Cloud, and Land Elevation Satellite 2
IFS........................ Integrated Forecasting System
IR .... Infrared
L1 .... Level 1
L1b .... Level 1b
L2 .... Level 2
MOSAiC .... Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NASA................... National Aeronautics and Space Administration
NEMO.................. Nucleus for European Modelling of the Ocean
NEMOVAR .... Variational DA software for the NEMO model
NIR....................... Near-infrared
NWP..................... Numerical weather prediction
O-B....................... Observation-minus-background
ODB .... Observation Database
ORAS6................. Ocean Reanalysis System 6
OSI SAF............... Ocean and Sea Ice Satellite Application Facility

PIOMAS .... Pan-Arctic Ice Ocean Modeling and Assimilation System
REQ .... Requirement
RFI .... Radio frequency interference
RT .... Radiative transfer
RTTOV .... Radiative Transfer for TOVS
SAR...................... Synthetic-aperture radar
SARAL .... Satellite for Argos and AltiKa
SI^3......................... Sea Ice Modelling Integrated Initiative
SIC .... Sea-ice concentration
SIE .... Sea-ice extent
SIT .... Sea-ice thickness
SMAP................... Soil Moisture Active Passive
SMMR .... Scanning Multichannel Microwave Radiometer
SMOS................... Soil Moisture and Ocean Salinity
SSM/I .... Special Sensor Microwave/Imager
SSMIS .... Special Sensor Microwave Imager/Sounder
SST....................... Sea-surface temperature
TL......................... Tangent-linear
WMO .... World Meteorological Organization
WP .... Work Package

1. Introduction and scope

This report outlines plans for activities to be performed in the first phase of the Data Assimilation and Numerical Testing for Copernicus Expansion Missions (DANTEX) project for the Copernicus Imaging Microwave Radiometer (CIMR) and Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL). In order to put these plans in context, the report first provides a non-exhaustive review of the state of the art for radiative transfer (RT) models, tools and data assimilation (DA) techniques applicable to CIMR and CRISTAL, focusing primarily on the numerical weather prediction (NWP) system at the European Centre for Medium-Range Weather Forecasts (ECMWF). It then gives an overview of wider long-term developments relevant to the exploitation of CIMR and CRISTAL observations, before outlining a roadmap of specific CIMR- and CRISTAL-related activities to be performed during the current phase of the DANTEX project. The aim of the developments planned here is to prepare and advance scientific capabilities for the exploitation of CIMR and CRISTAL-like observations in ECMWF's coupled DA system, with a particular focus on the cryosphere. As agreed in the DANTEX project contract, the following list of geophysical variables in the cryosphere are considered:

- Sea ice concentration (SIC)
- Sea ice extent (SIE)
- Sea ice thickness (SIT)
- Snow depth
- Surface elevation of polar glaciers

Information on SIC, SIE and SIT can be provided by CIMR, whereas CRISTAL provides information on SIT, snow depth and surface elevation. It should be noted that SIE is a diagnostic variable derived from SIC based on an SIC threshold, which is usually taken to be 15%[1]. The representation of glaciers and ice sheets in the current ECMWF system is not mature enough to enable the exploitation of satellite data to constrain polar glaciers. Therefore, the work conducted in DANTEX will focus on SIC, SIE, SIT and snow depth.

At ECMWF, the general aim is to assimilate observations with as little processing as possible. For satellite observations this means using instrument data (level 1 (L1) in World Meteorological Organization (WMO) terms) as opposed to retrieved geophysical products (level 2 (L2) in WMO terms). This acknowledges that satellite instruments are sensitive to many different aspects of the earth system and not just the target geophysical variables. The assimilation of instrument data (level 1) means that all the information can potentially be used, not just the narrower list of target geophysical variables (as

[1] The definition of open water (freely navigable ocean) uses a threshold of 10% SIC (World Meteorological Organization, 2014). On the other hand, some studies use a threshold of 20% to evaluate the sea-ice edge (e.g. Day et al., 2022).

available at level 2). This approach also allows more flexibility for the DA system to respond (possibly exploiting information from different Earth system components) and make the accounting of observation errors simpler. Following this approach, for CIMR, we will be assimilating radiances. On the other hand, for CRISTAL, the aim for the current phase of the project is to assimilate freeboard measurements, with the understanding that this is a tractable stepping stone towards fuller exploitation of data provided by the instruments on board the satellite. In any case, whatever the assimilated variable is, the target geophysical variables (SIC, SIT etc.) are produced by the DA system analysis. Such geophysical variables will also be featured in forecast products.

2. State of the art on Earth system prediction and assimilation for the cryosphere

The ECMWF NWP system uses a coupled modelling approach that represents the complex interactions and feedback mechanisms between atmosphere, land, ocean, sea ice, and waves. Dedicated advanced DA systems are used to initialise the model prognostic variables of each component (de Rosnay et al., 2022), as illustrated in Figure 1. Here we describe the version of the NWP system that will be implemented operationally in autumn 2025 as cycle 50r1 of the Integrated Forecasting System (IFS). The components of this coupled NWP system of particular relevance to this part of the DANTEX work are:

- **Atmospheric DA system**: This provides a statistically optimal estimate of the atmospheric state at analysis time by combining a short-range forecast and a comprehensive set of observations. It uses an incremental four-dimensional variational (4D-Var) DA scheme (Rabier et al., 2000), with an outer-loop resolution of TCo1279 in its high-resolution version and four inner-loop minimisations at resolutions of TL255/319/399/511 (approximately 80/60/50/40 km). Main analyses are performed every 12 hours using observations covering a 12-hour window. The background-error statistics for this 4D-Var system are provided by an Ensemble of Data Assimilations (EDA; Bonavita et al., 2016) based on a set of 50 independent, stochastically perturbed 4D-Var analyses run at the same resolution. In Figure 1, this system is labelled as “4D-Var OOPSVAR”.
- **Ocean and sea-ice analysis system**: A stand-alone ocean and sea-ice (re)analysis ORAS6 (Ocean Reanalysis System 6) supports medium-range to seasonal forecasts. It uses a five-day assimilation window and a bespoke configuration of NEMOVAR, the variational DA software for the NEMO (Nucleus for European Modelling of the Ocean) model. In the ECMWF implementation, a three-dimensional variational (3D-Var) DA scheme with first guess at appropriate time (FGAT) is used, with a hybrid ensemble-variational approach. In Figure 1, This system is labelled as “ORAS6”.
- **Ocean and sea-ice DA system in the main assimilation window**: The system includes coupled DA between the atmospheric and ocean/sea-ice components. A 12-hourly ocean/sea-

ice analysis using NEMOVAR (labelled as "3D-Var NEMOVAR" in Figure 1), which allows the ocean and sea-ice states to be further updated using the latest available observations. This new ocean and sea-ice analysis will run in parallel to the atmospheric DA system. Exchange of information between the atmosphere and ocean/sea-ice will take place during the coupled trajectory integrations.

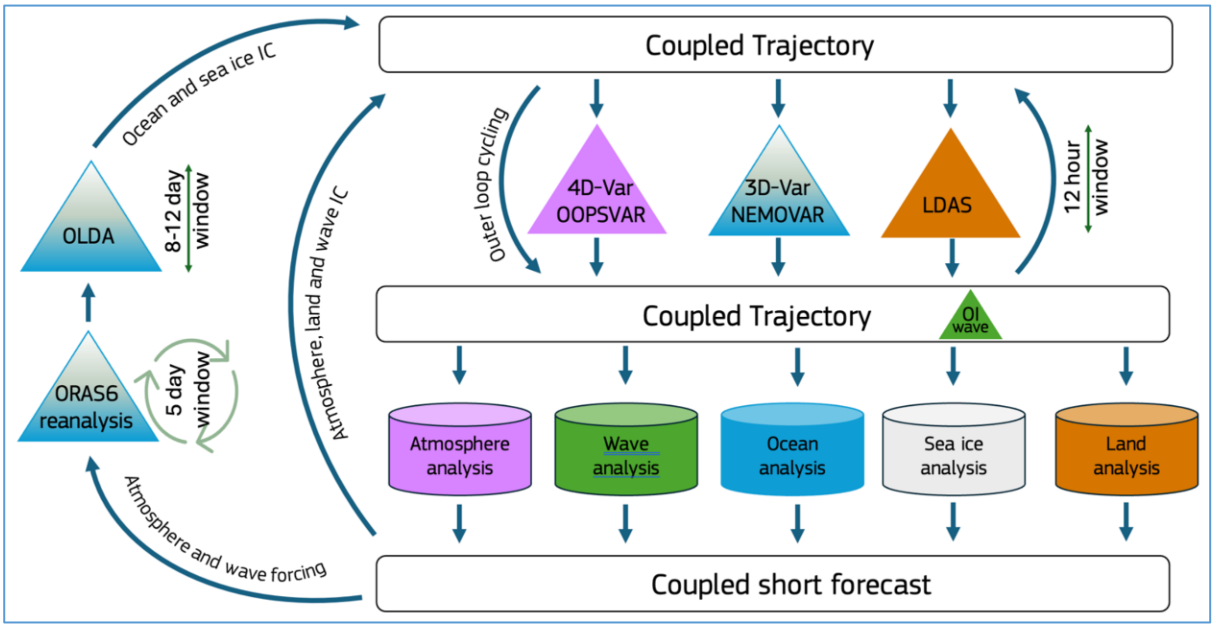

Figure 1: Schematic of the ECMWF DA system relevant to DANTEX. Within the framework of incremental variational DA, multiple coupled outer loops are used, with separate minimisations/analyses made for the different Earth system components. This system is anchored by an ocean/sea-ice reanalysis, which is driven by atmospheric and wave forcing, and an NRT ocean/sea-ice DA system.

In the following, we will describe in further detail aspects of the ECMWF DA system relevant to the CIMR and CRISTAL parts of the DANTEX project. We will first summarise approaches used for cryosphere modelling, before presenting an overview of the available observation sources related to the cryosphere. This is followed by an overview of the operational configuration of our DA system for the cryosphere, put into context with the approaches of other state-of-the-art systems.

2.1 Cryosphere modelling

The benchmark ocean and sea-ice DA and modelling system for this project is ORAS6 (Zuo et al., 2024). ORAS6 uses a multi-category sea-ice model SI^3 (Sea Ice Modelling Integrated Initiative) coupled to version 4 of the NEMO ocean model (Madec and the NEMO System Team, 2019). The ocean model resolution is 0.25° in the horizontal with 75 levels in the vertical, with a level spacing of 1 m at the surface. The SI^3 sea-ice model combines the conservation of momentum for viscous-plastic continuum, energy and salt-conserving halo-thermodynamics (Vancoppenolle et al., 2023). SI^3 updates the thermodynamic scheme considerably by making use of a multi-category formulation, prognostic salinity and a melt melt-pond parametrization. In the ORAS6 system, the SI^3 model has been developed with five thickness categories, each with four thermodynamic layers and a single snow layer on the top. This change in model formulation required a significant change in the way sea-ice DA increments are applied. In particular, care needs to be taken to ensure the application of single-category concentration increments into the multi-category model does not unduly change the model ice thickness. In SI^3, snow is assumed to be fresh with constant density (330 kg/m^3) and thermal conductivity, while sea ice is assumed to be a mushy layer of constant-density (917 kg/m^3) mixture of pure ice and saline brine in thermodynamic equilibrium.

Other multi-category sea-ice models like CICE (Los Alamos Sea Ice Model; see Hunke et al., 2015) are also widely used around the world, for example, in the UK Met Office (see Blockley et al., 2014). Like SI^3, CICE also uses five thickness categories with a single snow layer on top, and an elastic-viscous-plastic model to calculate ice drift. PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System) is another important coupled ocean and sea-ice model, especially in SIT works (e.g. Cocetta et al., 2024). PIOMAS utilises more sea-ice thickness categories (12 categories) within its sea-ice model. However, its ocean model, which employs only 13 vertical levels (Zhang et al., 2013), exhibits reduced capabilities compared to the NEMO ocean model (version 4) used in the ORAS6 system. Attempts have also been made to use a one-dimensional Lagrangian thermodynamic model of sea ice to simulate passive microwave emissions in the winter Arctic (see Kang et al., 2021). It was found that such a model did a reasonably good job to reproduce microwave emission signatures of sea ice when coupled to a RT scheme, which can be useful for developing observation operators for CIMR. However, this model cannot provide reliable estimation of ice freeboard and snow thickness due to the lack of dynamical processes for sea ice, so a full dynamical sea ice model such as SI^3 is needed to represent CRISTAL data.

For the ECMWF atmospheric model, a recent innovation relating to the cryosphere has been to represent the effects of snow on sea ice (Arduini et al., 2022), and this is part of the baseline cycle 50r1 operational system described here. The lack of representing snow on sea ice previously caused a warm bias in skin temperatures of up to 5°C to 10°C, which has also been noted for ERA5 and ERA-Interim reanalyses (Batrak and Muller, 2019). Arduini et al. (2022) have shown that representing snow insulation effects is essential for capturing the surface temperature variability over sea ice and its response to changes in atmospheric forcing over the Arctic.

Results from the APPLICATE (Advanced Prediction in Polar Regions and Beyond: Modelling, Observing System Design and Linkages associated with a Changing Arctic Climate) project, funded by the Horizon 2020 programme, indicated that although substantial efforts have been devoted to develop and test new parametrizations and model features to refine the representation of sea ice (e.g. SIT distribution, landfast ice, snow on sea ice, form drag or melt ponds), the outcome in terms of improving both NWP and seasonal systems was mixed (Ortega et al., 2022). This was due to pre-existing and partly compensating systematic model errors, unbalanced physics and numerical issues disguising the improvements. Furthermore, coupling between the ocean, sea ice and atmosphere introduced new systematic errors that were not present in stand-alone ocean–sea-ice systems. Considerable model biases over the Arctic for many state-of-the-art NWP and climate systems limit their predictive capacity and credibility to assess changes. On the other hand, increasing both the horizontal and vertical model resolution of regional Arctic NWP systems could improve forecasts close to the surface.

2.2 Cryosphere observations

Satellite observations at microwave frequencies are the primary means of observing sea ice. Microwave observations can use both passive and active configurations, the latter including radar altimetry, scatterometry and synthetic-aperture radar (SAR). In this report, passive microwave and radar altimetry are the exclusive focus, targeting the CIMR and CRISTAL missions respectively. Scatterometer backscatter measurements are not covered further here, but they are likely to play an increasing role in cryospheric DA in the future, since they are already used extensively for the characterisation of ice age/type and the detection of ice edge (Breivik et al., 2012). SAR (Lyu et al., 2022), like Sentinel-1, provides higher spatial resolution but with limited coverage of the polar regions on a daily basis, and is likely to have slower uptake in data assimilation. Observations in the infrared (IR) or the visible/near-infrared (NIR) part of the electromagnetic (EM) spectrum can also be used for the retrieval of cryospheric variables. IR and visible observations provide typically finer spatial resolution than in the microwave part of the EM spectrum. However, due to atmospheric contributions to the measured signal (especially in the case of optically thick clouds where the surface becomes invisible) and the need for solar illumination for passive Visible/NIR instruments (which is absent during the long polar nights), these observations suffer from significant spatial and/or temporal gaps. Microwave observations are significantly less affected by these issues. Since they can penetrate through snow and sea ice, they are widely used to retrieve both bulk and surface cryospheric variables over the polar regions.

2.2.1 Sea-ice concentration from passive microwave

The ability to infer sea-ice concentration information from passive microwave observations is based on the different surface emission characteristics of sea ice and ocean water. Emission and scattering signatures are affected by the presence of pure ice, brine and air bubbles. As that composition changes over time (e.g. due to desalination as result of expulsion of brine towards water at the bottom of the ice pack), first-year and multi-year ice differ in microwave emission signatures (Rückert et al., 2023). For first-year ice, the emitting layer is nearly frequency-independent between 6 GHz and 37 GHz at about 5 cm below the snow layer, but for multi-year ice there is a broad distribution of weighting functions: for 6 GHz, it peaks at around 30 cm below the snow layer, whereas for 37 GHz, it peaks at about 10 cm below the snow layer (Lee et al., 2017). Because the temperatures of sea ice and snow vary with depth (Vancoppenolle et al., 2023), different microwave frequencies see different sea-ice temperatures. Apart from emissions from sea ice, snow on top of sea ice or superimposed ice (i.e. water from snow melt percolating down and refreezing by contact with sea ice), scattering contributes to the signal measured by microwave instruments as well, which is indicated by a decrease of brightness temperature with increasing frequencies in CIMR channels (Soriot et al., 2022).

SIC in the satellite era has traditionally been retrieved from passive microwave radiometers using measurements at around 19 and 37 GHz (Ivanova et al., 2014; Kern et al., 2019). Lower frequencies (e.g. 6 GHz) are less affected by the atmosphere but have a larger field of view, whereas higher frequencies (e.g. 89 GHz) have the opposite characteristics. The continuing focus on 19 and 37 GHz in SIC retrievals is particularly driven by climate applications where historical continuity is important.

Typical examples of SIC algorithms for passive microwave observations using instruments like the Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), Special Sensor Microwave Imager/Sounder (SSMIS), Advanced Microwave Scanning Radiometer for EOS (AMSR-E) or Advanced Microwave Scanning Radiometer 2 (AMSR2) are those developed within the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) Ocean and Sea Ice Satellite Application Facility (OSI SAF)[2] and the European Space Agency (ESA) Climate Change Initiative (CCI) projects. They are based on dynamic tie points, which capture the time-evolution of surface characteristics of the ice cover and accommodate potential calibration differences between satellite missions (Lavergne et al., 2019). They are characterised by a hybrid method, combining one algorithm which performs better over open water and low SIC, with one which is tuned to perform better over closed ice and high SIC, using brightness temperatures at three channels: 19 GHz with vertical polarisation and 37 GHz with both vertical and horizontal polarisations (in the case of AMSR-E or AMSR2 the 6 GHz is also used instead of the 19 GHz). Note that using the 6 GHz channel in place of the 19 GHz for AMSR-E or AMSR2 leads to coarser spatial resolution of the data record from 25 to 50 km, but at the same time it decreases the impact of the atmosphere on the SIC retrieval (Scarlat et al., 2020).

A recent evaluation of tie-point based SIC retrievals by Ivanova et al. (2014) and Kern et al. (2019) highlighted a few issues with these retrievals. The retrievals show differences due to the choice of the channels used, the dataset used for training the tie points, sensitivities to changes in physical temperature of the surface, and detection of spurious SIC values over open water resulting from atmospheric effects through wind, water vapour and/or cloud liquid water. There are also differences regarding how the algorithms handle surface emissivity variations or variations in the atmospheric influence (Kern et al., 2019). The retrieval of sea-ice properties is more complicated during summer than winter because of wet snow, melt ponds and thin ice-water mixtures (Ivanova et al., 2014). Finally, the brightness temperature contrast between sea-ice/land and open water leads to the need to apply land-ocean spillover masks along coastlines to accommodate for the coarse footprint of the instruments. All these issues suggest that SIC should be retrieved using a more physical approach than the tie-point method. If we know the surface emissivity and emitting temperature of sea ice and the surrounding ocean, and if there is radiative contrast between the two, then we can physically infer SIC. To deal with atmospheric effects we can use an all-sky atmospheric radiative transfer model as part of the retrieval, along with the latest temperature, moisture and hydrometeor profiles from ECMWF analyses. This approach is best implemented within a coupled DA system, where the atmosphere and surface analyses can be inferred simultaneously and where the retrieval benefits from all other observations with sensitivity to the same areas.

Such a physics-based approach is implemented in the cycle 50r1 configuration of the IFS and provides SIC retrievals, which are made in the atmospheric DA component, to the ocean DA component. One advantage of this approach over external SIC retrievals, beyond the move from tie points to using physical RT modelling, is to eliminate the time delay between the actual observation time and the time of its use in the forecasting system.

The physical SIC retrieval in the IFS atmospheric component was not easy to implement because of the poor knowledge of the micro-and macro-physical properties of sea ice and any snow on top of it, as well as the poor knowledge of how to convert these properties into a description of radiative transfer

[2] See https://osi-saf.eumetsat.int for more details.

for these surfaces. Hence, the surface emissivity model for sea ice was developed within a hybrid physical and machine-learning model that simultaneously retrieves SIC and sea-ice emissivity, using observations from AMSR2 and input from the atmospheric weather forecasting system (Geer, 2024a). By allowing the assimilation of GMI and AMSR2 observations over sea ice areas for the first time, this technique not only improves variables at the interfaces, but also the atmospheric forecasts out to day 4 in the Southern Ocean (Geer, 2024b).

2.2.2 Sea-ice thickness from passive microwave

While SIC has been the main focus of passive microwave developments so far, SIT products are also becoming important. Sea-ice layers less than around 1 m thick can become partially transparent at low microwave frequencies. This allows some radiation from the ocean to penetrate the ice, meaning that it is possible to infer SIT if there is also a temperature contrast between the ice and ocean. SIT observations help close the ice volume budget, which in the Arctic is characterised by a decadal-scale decline, especially in autumn (Kacimi and Kwok, 2022). The assimilation of SIC data year-round and SIT data during the cold season (October to April for the Arctic) has also demonstrated the importance of SIT for Earth system forecasts (Fritzner et al., 2019; Lee and Ham, 2023). This is due to SIT anomalies having longer memory (i.e. months) than SIC (i.e. days). Recently, year-round SIT datasets have also become available (Landy et al., 2022).

SIT information from passive microwave instruments complements that from altimeters, which historically have been the main source of SIT information (see also Section 2.2.3). SIT retrieved from microwave altimeters is characterised by uncertainties that rise asymptotically towards thinner ice less than 1 m thick (Ricker et al., 2017). On the other hand, radiometers measuring at the L-band, such as Soil Moisture and Ocean Salinity (SMOS; Kerr et al., 2010) and Soil Moisture Active Passive (SMAP; Entekhabi et al., 2010), can retrieve thin SIT up to a thickness of 0.5 m to 1 m, as the signal saturates above this threshold (Tian-Kunze et al., 2014; Paţilea et al., 2019). However, this is roughly the thickness range over which the sea-ice albedo changes drastically with SIT (Vancoppenolle et al., 2023); this thickness range, together with sea-ice leads, plays an important role in RT over the polar regions (Marcq and Weiss, 2012). Thus, radiometers are not only complementary to altimeters regarding SIT, but most importantly they provide SIT information in the marginal ice zone where sea ice is most variable. Passive microwave sensors also provide full coverage of the polar regions on sub-daily timescales, which is very useful for weather prediction and ship navigation in the Arctic. However, the sensitivity of the brightness temperature to SIT disappears as the temperature of the ice approaches the melting point. This means that the SIT retrieval from L-band measurements is in general limited to the cold season which, in the case of the Arctic, is also affected by radio frequency interference (RFI) contamination (Kaleschke et al., 2024).

2.2.3 Sea-ice and snow thickness from altimetry missions

The launch of the ESA CryoSat-2 satellite in 2010 (Wingham et al., 2006) has opened new avenues for observing, monitoring and understanding the cryospheric component of the Earth system beyond the monitoring and assimilation of SIC. Unlike earlier missions, the high orbital inclination of CryoSat-2 means that it is able to take observations up to 88° latitude. This substantially reduces the area of the so-called "pole hole", where satellite observations are unavailable, and makes a crucial difference for cryospheric monitoring in the Arctic, since a much larger part of the Arctic Ocean can now be observed by CryoSat-2.

Being a SAR altimeter, CryoSat-2 can measure sea-ice freeboard by comparing the altimeter range of a signal reflected by the ice surface and the range of another signal reflected by the local sea surface in the ice leads. This allows one to infer SIT by applying the hydrostatic equilibrium constraint (Tilling et al., 2016) and making assumptions about snow depth over sea ice as well as various densities. The conversion of CryoSat-2 data from freeboard to thickness is routinely performed by centres such as the Centre for Polar Observation and Modelling (Tilling et al., 2016). The snow depth and the densities are often taken from a climatological dataset or a model integration or, in the case of the densities, are assumed constant (Ricker et al., 2017; Fiedler et al., 2022). The use of a climatological snow depth in particular could introduce considerable uncertainties to the retrieved value of SIT. Moreover, snow on sea ice could slow down the speed of the altimeter signal. A correction to the altimeter range, and hence the sea ice freeboard is needed, but the treatment could be rather empirical (Fiedler et al., 2022). This is another source of uncertainty to the SIT retrieval algorithm.

In spite of such deficiencies, CryoSat-2 SIT data are still deemed to be most accurate when the retrieved SIT is in the range of 1.5 m to 3 m (Fiedler et al., 2022; Mignac et al., 2022). While the accuracy gradually degrades at thicker ice, the degradation is most significant over thin ice, to a point where CryoSat-2 SIT data cannot be relied upon when the retrieved SIT is shallower than 1 m (Ricker et al., 2014; Ricker et al., 2017; Fiedler et al., 2022). This is due to large errors resulting from the retrieval of small freeboard elevations that are only marginally distinguishable from the sea level (Ricker et al., 2017). Because of the unreliability of CryoSat-2 SIT data over thin ice, such data are only available for the Arctic region in the winter (October to April). However, even in the case of Arctic winter, SMOS SIT data are used to complement CryoSat-2, especially in the marginal seas where ice is generally shallower. A combined retrieval product between CryoSat-2 and SMOS is often used for monitoring (Ricker et al., 2017).

As mentioned earlier, the more accurate estimation of snow depth over sea ice will improve SIT retrieval calculations. Apart from retrievals using passive microwave radiometry (Braakmann-Folgmann and Donlon, 2019), snow depth over sea ice can also be inferred using radar altimetry. Armitage and Ridout (2015) have compared sea-ice freeboard data between CryoSat-2, which uses a Ku-band (13.5 GHz) radar altimeter, and the Ka-band (35.7 GHz) altimeter AltiKa (Altimeter in Ka-band) on board SARAL (Satellite for Argos and AltiKa; see SARAL/AltiKa Products Handbook, 2021). This study has shed light on the difference in snow-penetration properties between the two radar frequencies. Ku-band signals can largely penetrate through snow (but not sea ice), whereas pulses from the Ka band are primarily reflected near the middle of the snow pack. Such difference in properties has in turn opened the possibility of estimating snow depth over sea ice by exploiting information from co-located Ka-band and Ku-band altimeter measurements. Garnier et al. (2021) have demonstrated this concept by considering Ka-band data from AltiKa alongside Ku-band data from CryoSat-2, and have shown that the resulting estimates of snow depth are consistent with validation data from several independent sources. That being said, their study is limited by the fact that SARAL/AltiKa has a smaller coverage than CryoSat-2 (up to 81.5°N/S compared to 88°N/S), which means that not too many co-located observations are available. This is especially the case since CryoSat-2 data are unreliable over thin ice, which tends to be more prevalent at lower latitudes.

The upcoming CRISTAL instrument by ESA will be able to fill in such gaps (Kern et al., 2020). With a dual Ka–Ku band altimeter on board, the Ka- and Ku-band observations will be spatial-temporally co-located by default, so CRISTAL will be able to provide a much better coverage of snow depth observations over sea ice. Moreover, this information will be used alongside the Ku-band freeboard measurements to produce improved estimates of SIT. Finally, like CryoSat-2, CRISTAL will have an 92° orbital inclination, meaning that much of the Arctic Ocean will be observed (up to 88°N). Therefore, the wealth of information inferable from CRISTAL can potentially improve ECMWF's prediction of the cryosphere and other parts of the Earth system through the assimilation of such information into the Centre's NWP and ocean/sea-ice forecasting systems.

2.3 Operational cryosphere DA systems

2.3.1 Ocean and sea-ice DA system

ORAS6 is the benchmark ECMWF ocean and sea-ice DA system used in the DANTEX work. Currently, the sea-ice DA system in ORAS6 only assimilates level-3 SIC data directly from OSI SAF. It needs to be adapted to account for new prognostic variables in the SI^3 model, as well as for the concept of representing the ice with multiple thickness categories (Browne et al., 2025). The assimilation system for the ECMWF ocean/sea-ice state uses flow-dependent error covariances via a hybrid ensemble-variational 3D-Var-FGAT configuration of NEMOVAR (see Chrust et al., 2024). For the sea-ice component, it is configured with a control variable representing grid-box-averaged SIC, whereas the model prognostic variables represent a subgrid-scale distribution of SIC with different thickness categories. Care has been taken to ensure the application of single-category concentration increments into the multi-category model does not unduly change the model's SIT. ORAS6 uses a single minimisation of the cost function for both sea-ice and ocean variables, but without specifying cross-covariances between SIC and other variables. Assimilation of SIC in ORAS6 has no direct impact on SIT. However, SIC assimilation increments directly change the equivalent ice thickness, as discussed by Tietsche et al. (2013).

Functionality to assimilate thickness or freeboard information in the ECMWF system is not yet available. Attempts have been made at ECMWF to constrain SIT states by nudging model background SIT towards a merged reconstructed SIT dataset CS2SMOS (CryoSat-2–SMOS; see Ricker et al., 2017). This has demonstrated that the prediction skill of pan-Arctic sea ice could be improved for up to 7 months of lead time with better-constrained initial conditions of SIT (Balan-Sarojini et al., 2021).

2.3.2 Coupled system

A further aspect of coupling is to be implemented in cycle 50r1 of ECMWF's IFS in autumn 2025. Within the 12-hour-window 4D-Var system that produces initial conditions for the forecast, the non-linear model integrations of the atmosphere will be coupled to the ocean and sea-ice model. This means that the prognostic variables of the sea ice model will be available to the observation operators used in the atmospheric 4D-Var system, and the surface state will be dynamically more consistent with the atmosphere. In this respect the coupled system will be similar to CERA-SAT (Coupled ECMWF Reanalysis for the Satellite Era; see Schepers et al., 2018). Initial conditions of the ocean and sea ice for this coupled stream are reinitialised from ORAS6 once daily, anchoring the system to one that has long-term proven stability.

A recent extension has been to use consistent coupled observation operators whilst maintaining separate minimisations for the atmosphere and the ocean/sea-ice. This allows the use of L1 observations to constrain the ocean and sea-ice state, which is done through the use of intermediate (or pseudo-) observations retrieved by the atmospheric component. The system to use coupled observation operators allows the extraction of SIC information from passive microwave instruments as well as sea-surface temperature (SST) information from both passive microwave and IR instruments.

In this system, SIC (as well as SST) observations derived from microwave imagers in the atmospheric DA (Geer, 2024b) are assimilated as pseudo-observations within NEMOVAR. The assimilation of these SIC pseudo-observations yields beneficial impacts in fits to significant wave height measurements (the representation of which is strongly controlled by the presence or absence of sea ice) and more generally improvements in the quality of the forecasts in polar regions. However, there are also mean shifts in SIC and resulting mean changes in lower tropospheric temperatures. These are likely a result of the shift from one SIC product (OSI SAF in ORAS6) to another (ECMWF retrievals in the atmospheric cycling), and it is hard to say if one or other resulting climatology is better.

A few other centres around the world have developed capacity to assimilate SIT or freeboard data. For example, the UK Met Office is capable of assimilating retrieved SIT data from CryoSat-2 or the CS2SMOS merged product in a separate minimisation specifically for SIT using NEMOVAR (Fiedler et al., 2022; Mignac et al., 2022). However, the implementation does not allow for a joint minimisation with other variables such as SIC. Mercator Ocean International have recently developed the capacity to assimilate along-track freeboard and snow data (Chenal et al., 2024) using the SEEK filter methodology but notably constraining NEMO4/SI[3] (a very similar model configuration to the one used at ECMWF). The SEEK filter’s use of ensemble/pre-computed covariances leads to a natural choice of sea-ice volume as a control variable. With a variational approach of DA being used at ECMWF instead, other issues such as separability/diagonalisability of the system may lead to different choices of control variables.

3. Status of RT models, tools and DA for the cryosphere

3.1 Passive microwave

The assimilation of satellite radiances for the cryosphere will be carried out at ECMWF within the atmospheric DA system, where the sophisticated RT model RTTOV (Radiative Transfer for TOVS) is already used to exploit the atmospheric information content of satellite radiances (Saunders et al., 2018). Within RTTOV, the ocean surface emissivity is modelled using the SURFEM emissivity model (Kilic et al., 2023), a neural network fit to the reference PARMIO emissivity model (Dinnat et al., 2023). Both RTTOV and SURFEM already cover the full range of frequencies needed for CIMR. The surface RT over land, snow and sea-ice surfaces in atmospheric DA systems has traditionally assumed specular reflection from an impenetrable surface. In this assumption, the surface can be described by its skin temperature and a surface emissivity (with the surface reflectivity being 1 minus the surface emissivity). The skin temperature usually comes from the forecast model and is assumed perfect. The surface emissivity comes from atlases, from dynamic surface emissivity retrievals (e.g. Karbou et al., 2006) or from more sophisticated surface emissivity models. Within DANTEX, the skin temperature/emissivity approach will be broadened to allow the inference of SIC and possibly SIT as part of the atmospheric DA process.

Within real sea ice and snow layers, emission, reflection and scattering occur well below the surface, meaning that the physical emitting temperature may be very different from the skin temperature. A common approach is hence to use an "effective emissivity", i.e. a surface emissivity that together with an effective skin temperature determines the emitted radiance and reflection of the surface in the specular reflection approach. While it is physically possible for such effective emissivity to go above 1 (in cases where the emission is coming from much warmer ice or snowpack layers under a very cold surface), emissivities of greater than 1 are generally disallowed in atmospheric RT models. The more general limitations of the effective emissivity approach are known to cause errors in DA (e.g. Bormann et al., 2017). However, the relevant observations provide benefit in the atmospheric system despite the errors, and a more sophisticated RT approach is unlikely to be used within the current phase of the DANTEX project.

For microwave sounders, a further refinement of the specular approach has been to consider partial Lambertian reflection. Specular reflection is relatively indistinguishable from Lambertian reflection at microwave imager zenith angles (around 53°) but becomes important towards nadir, where it can enhance the reflected component (since it redirects warmer radiation travelling at slant beam angles). ECMWF has implemented a specular correction for the assimilation of ATMS radiances over snow surfaces (Bormann, 2022). This suggests that future developments in sea-ice RT should also allow a mix of specular and Lambertian representations.

Over snow-covered land surfaces, ECMWF has attempted to take the output of the physical land surface snow model to drive a physical snow RT model (Hirahara et al., 2020). Precisely, this used the HUT snow emission model within the broader surface RT package CMEM. Matches to AMSR2 observations were seen to be reasonably accurate below 20 GHz but were problematic at higher frequencies. The likely explanations for poor performance above 20 GHz come from both the forecast model representation of the snow, which is lacking any description of crucial microstructural aspects of the snow (e.g. grain size) as well as limitations in the current RT modelling within the snowpack. These conclusions are likely equally applicable to sea-ice areas. For these reasons, efforts to use physical modelling of cryosphere radiation processes as part of the forward modelling of microwave observations has not yet taken off at weather centres.

Within the research community, over sea ice, a few state-of-the-art studies have nevertheless been able to replicate passive microwave observations reasonably well over snow and sea-ice surfaces using physical modelling. One example of a successful forward modelling study is by Kang et al. (2023). This work uses a Lagrangian sea-ice forecast model to provide snow and ice layer depths, temperature, density, salinity and grain size. A snow RT model is then used to simulate observed brightness temperatures. The limitations are the need to empirically determine the ice and snow optical properties, and the rather limited successful test for sea ice in Arctic winter. Rückert et al. (2023) were also able to get good agreement between physically simulated and observed microwave brightness temperatures, but again the work was limited to the Arctic winter. Sandells et al. (2024) got good agreement with observations up to 200 GHz over dry Arctic land snow surfaces, but this relied on detailed snow pit measurements to determine the grain size. These studies suggest that weather forecasting centres should in future be able to use physical RT models to assimilate passive microwave observations of the cryosphere. However, this approach is not yet practical for weather forecasting. For example, these studies are restricted mainly to the winter season, typically to the Arctic and it is generally expected that these models are not yet able to cope with the melting and summer seasons. Also, information on the relevant detailed microstructural characteristics of sea ice and snow is not yet available from the current generation of operational sea-ice and snow modelling at NWP centres.

Since the implementation of cycle 49r1 of the IFS in November 2024, ECMWF is now assimilating passive microwave radiances from AMSR2 and GMI over sea-ice surfaces (Geer, 2024b). This relies on a hybrid physical-empirical technique to provide the sea-ice emissivity that is valid across all seasons and both hemispheres. The unknown microstructural details of sea ice and its snow cover are represented by three empirical variables at each location, which are retrieved as part of the DA process. This means the surface emissivity model is dynamically adjusted to fit each observation location. As described earlier, the underlying structure of the empirical surface emissivity model is trained against one year of AMSR2 observations (Geer, 2024a). This approach supersedes the dynamic emissivity technique and finally allows the assimilation of window channels to improve the quality of the atmospheric analysis. In addition, it enables an estimation of SIC to be made at each AMSR2 and GMI observation location, together with the SURFEM-based ocean emissivity.

The DANTEX baseline, cycle 50r1 of the IFS, introduces the assimilation of ECMWF's SIC estimate from AMSR2 into the coupled NEMOVAR analysis. Cycle 50r1 also includes an improved version ("v2") of the sea-ice emissivity framework that was introduced at 49r1 (referred to as "v1"). The original sea-ice emissivity model covered only 10 to 89 GHz, but v2 will extend that up to 183 GHz, based on a training phase simultaneously fitting AMSR2, GMI and SSMIS observations. The original model was linear, whereas the new model uses a two-layer non-linear neural network to determine the sea-ice emissivity as a function of the 3 input empirical variables. The "v2" emissivity framework enables the assimilation of the 166 GHz and lowest-peaking 183 GHz channels of GMI over sea-ice surfaces for the first time. It provides better fit to observations in the background and analysis simulations, and it fixes some problems of the earlier model that tended to generate incorrectly low SIC retrievals over multi-year ice surfaces. The “v2” sea ice emissivity model will be further extended to support the 6/7 GHz channels of AMSR2 and the 1.4 GHz channels of SMAP as part of the DANTEX project.

3.2 Radar altimetry

Radar altimetry has been able to measure sea-ice freeboard since the launch of CryoSat-2 in 2010. By measuring the altimeter range of the sea-ice surface and the altimeter range of open water leads, the sea-ice freeboard, i.e. the height of sea ice above the local water level, can be inferred by taking the difference of the two measurements. Which surface is being detected is discriminated by the “pulse peakiness” of the altimeter waveform, with thresholds specific to a given instrument.

CryoSat-2 is an ESA Earth Explorer mission with a particularly high orbital inclination (92°), which means that it is able to cover most of the Arctic (up to 88°N). Products can be derived from other altimeter satellites, and there is now a 30-year freeboard dataset derived from ERS-1, ERS-2, Envisat and CryoSat-2 (Bocquet et al., 2024).

Challenges relating to freeboard estimation from altimeters include the limited inclination of low-Earth orbit altimetry platforms, the presence of melt ponds on sea ice in the summer season that alias into the estimation of the range of leads, and the snow loading in the southern hemisphere that can submerge sea ice and lead to incorrect range measurements of the sea-ice surface (Eicken et al., 1995).

Ku-band altimeter signals are sensitive to the sea-ice surface, as they penetrate the snow layer and are reflected by the snow-ice interface. Ka-band altimeters, on the other hand, are sensitive to both sea ice and any present snow layer. A Ka-band altimeter is flying on SARAL/AltiKa, and it is included in regular Operation IceBridge airborne campaigns conducted by the National Aeronautics and Space Administration (NASA). In that sense, Ka-band observations are similar to laser altimetry from the NASA ICESat-2 (Ice, Cloud, and Land Elevation Satellite 2) mission. Both Ku- and Ka-band altimeters undergo some amount of penetration into the surface and scattering, and corrections for these can be applied to reach target uncertainty estimates (Tonboe et al., 2021).

Meteorological and oceanographic applications of radar altimetry typically include the use of further processed data where SIT is derived from freeboard measurements. This derivation will depend on auxillary data related to snow loading as well as the densities of sea ice, water and snow.

Ku-band altimeters also have high freeboard uncertainties for low freeboard values. To ameliorate this, a merged product, CS2SMOS, has been produced, which is a combination of CryoSat-2 altimetry in regions of thick ice and SMOS-derived thickness in regions of thin ice. ECMWF has previously shown the positive potential impact of constraining a seasonal forecasting system with this data (Balan-Sarojini et al., 2021).

ECMWF has limited capacity, based on work done for sea-level anomaly data from Sentinel-3A/3B, to forward-model altimeter range observations. However, the accurate estimation of pulse peakiness is not possible at the existing resolution of the model, so the use of individual L1 observations of altimeter ranges over sea ice to extract SIT information will be a great challenge. However, forward models for grid-box-averaged values of sea-ice freeboard (Ku-band), snow freeboard (Ka-band) and snow depth are already in place. Similarly, a forward operator for grid-box-averaged SIT is also available. Thus, the assimilation of L2 retrievals of freeboard and snow depth is the most achievable goal within DANTEX.

However, there are a number of key components that are not yet in place to enable the assimilation of such information. Firstly, regular acquisition of existing data streams is not in place for freeboard data (e.g. from CryoSat-2). The existing control variables within the DA system have no sensitivity to thickness information, as they are only sensitive to SIC. Linearised observation operators, which are necessary for the variational assimilation of the data, are also yet to be implemented. Finally, there is no observation error model in place for altimeter observations of sea-ice freeboard.

4. Improvements to be implemented for the RT models, tools and DA for the cryosphere

We will now outline longer-term development plans for the evolution of ECMWF's coupled DA system as well as the use of passive microwave radiances and altimeter data. Aimed at optimising the exploitation of these key observations, the plans include improvements in RT modelling, the use of specific observations as well as the general DA system. The aims of this section are to put the developments performed within the current phase of DANTEX into a wider context and to provide a longer development horizon. Specific work plans within the current phase of DANTEX are laid out in Section 6.

4.1 CIMR

To summarise earlier sections, the current state of the art for using passive microwave data for the cryosphere in the ECMWF system is represented by the combination of ORAS6 and the outer-loop-coupled DA system that will go operational in autumn 2025. In terms of sea ice, the ORAS6 component maintains the backbone-cycled sea-ice model and assimilates OSI SAF SIC retrievals but no other sources of sea-ice data. However, the outer-loop-coupled system will assimilate AMSR2 and GMI radiances from 10 GHz to 183 GHz over sea ice within the atmospheric DA component. From this, the SIC retrieved at AMSR2 locations using the atmospheric component is assimilated as pseudo-observations within the ocean–sea-ice component of the outer-loop-coupled DA system. The first objective for exploiting CIMR data is therefore to include it within the same framework, i.e. to assimilate CIMR-like L1 radiances in the atmospheric data assimilation system and then to pass the retrieved SIC to the ocean–sea-ice component in the outer-loop-coupled DA system.

The main work required to implement CIMR-like data in this framework is to prepare the data processing (the technical framework) along with the observation operator, observation errors and quality control. The assimilation of channels at 10 GHz and above is already in place and demonstrated by AMSR2 and GMI, but for 1.4 GHz and 6/7 GHz it will require substantial new developments. Given that the current empirical sea-ice surface emissivity model is only valid down to 10 GHz, a main first step is to extend this model by retraining it down to 6/7 GHz and 1.4 GHz. Since the model is empirical, it requires existing observations at these frequencies, which can be provided by the AMSR2 6 GHz and 7 GHz channels along with SMAP for 1.4 GHz. Once the observation operator has been extended down to these frequencies, it will be possible to test the assimilation of SMAP and AMSR2 6/7 GHz channels in the ECMWF coupled DA system, with the impact measured using an assessment of the change in quality of atmospheric, sea-ice and ocean forecasts.

The initial system for exploiting CIMR-like data focuses on SIC. The exploitation of further information, such as SIT and snow depth (and even ice and snow temperature and microstructure) requires further development of the observation operator and the DA framework more widely. Some of these developments are done in parallel, outside the DANTEX project, and can hence only be incorporated into the exploitation of CIMR-like radiances in the current phase of DANTEX if they are sufficiently mature. The primary development requirement of these parallel activities is to move away from representing the surface RT using an effective emissivity and skin temperature. This requires implementing a multi-level snow RT model, and it requires methods for specifying the temperature and optical properties of each layer. The research community has seen good results with such models in the Arctic for typical winter snow and ice conditions, but the required inputs in terms of grain size profiles and other microstructural information are not present in the relevant ECMWF model components. Further, we need to support all seasons and locations. Hence we initially envisage using a simpler two-slab RT model that represents sea ice and snow with one layer each. The optical properties of the sea ice and snow will be empirically generated using a similar approach to the one used for sea-ice emissivity at the moment, for example, a mix of empirical and physical input state variables and a neural network model. With the multi-layer RT model of sea ice and snow in place, a primary target will be to extract SIT and to attempt to assimilate it in the outer-loop-coupled DA system in the same way as for SIC.

The creation of a microwave sea-ice training database will be essential to support all the above-mentioned developments. The requirements include:

- The training dataset should be based on the cycle 50r1 coupled model framework, which uses the new SI^3 model and the "snow on sea ice" scheme (which is part of the atmospheric model). The previous empirical sea-ice emissivity models were trained on an earlier version of the ECMWF system, which used a more limited description of sea ice and snow and produced a different climatology of sea-ice skin temperature due to the lack of snow on sea ice (e.g. Arduini et al., 2022).

- The previous training dataset was based on a single year, from July 2020 to June 2021. While this was mostly sufficient, experience has shown that some important sea ice conditions were not included in the training period because this was a colder year with less sea-ice loss than encountered more recently. Currently, for some specific identifiable conditions of summer sea ice, the assimilation of microwave radiances is not possible, so a quality control is applied. Hence, an aspiration is to extend the training database across multiple years, to include years with more and less significant sea-ice loss in the summer.

- The existing training dataset uses AMSR2, GMI and SSMIS, but only down to 10 GHz. It needs to be augmented by SMAP data at 1.4 GHz and by the AMSR2 6/7 GHz channels. A long-term aspiration would also be to include scatterometer backscatter measurements in the training dataset, since these offer unique information on the macro- and micro-physical structures of sea ice that also affect the passive microwave.

- The existing training dataset does not include information on the physical profile (e.g. temperature, density, layer thicknesses) of sea ice and snow. This should be included for three reasons:

    - As supporting information for interpreting the behaviour of the new version of the empirical sea-ice emissivity model: in the future, these variables can also be used to guide decisions on observation error and quality control, which can be explored using the database.

    - As possible physical inputs for the empirical sea-ice emissivity model, in the way that model skin temperature is a physical input in the current model. A particular advantage of the machine learning framework is that we can explore the use of various sets of input variables to identify which model variables are good predictors of microwave sea-ice emission and hence which variables might be best targeted for assimilation in future.

    - More generally, to test future DA strategies for the cryosphere outside the current DA system in the 1D context provided by the training database.

Beyond the above RT-related aspects, we expect that results from the current phase of DANTEX will also guide further development of the overall coupled DA framework, supporting an even fuller exploitation of CIMR in the future. Areas of possible development are the use of enhanced extended control vectors, improved observation operator coupling, or a different treatment of the control vector for coupling between the atmospheric and ocean–sea-ice components. As we gain further experience with coupled DA, some of these developments could at some stage obviate the use of pseudo-observations to transfer information from the atmospheric to the ocean–sea-ice component. The developments planned in the current phase of DANTEX are crucial stepping stones towards this.

4.2 CRISTAL

Currently, the only cryospheric variable assimilated in ECMWF's ocean–sea-ice DA system is SIC, in a single-category approach. When CRISTAL is launched, it will be able to provide measurements of sea-ice freeboard and estimates of snow depth over sea ice. Such data will complement SIC measurements from existing instruments as well as from CIMR. It is the ambition of ECMWF to exploit the additional data in both the stand-alone ocean–sea-ice DA system and the coupled DA system in the best possible way, so that sea ice can be more faithfully represented and predicted in Earth system models.

To achieve this, we will have to set up data processing chains for CRISTAL observations, which will include data acquisition, quality control and pre-processing (e.g. thinning and perturbation). Forward observation operators from multi-category SIC and SIV (sea-ice volume) model variables will be coded up, to enable comparison against CRISTAL-like sea-ice freeboard data. In addition, we will implement a tangent-linear (TL) version of the observation operators together with its adjoint (AD) code. Such TL and AD operators, which map a perturbation in model space into a perturbation in observation space and vice versa, are essential components of an incremental-formulation variational DA system such as NEMOVAR (see Mogensen et al., 2012).

On the other hand, significant NEMOVAR developments are also required to enable the assimilation of CRISTAL-like observations. The NEMOVAR control variables will need to be extended to be sensitive to new sea-ice freeboard and snow-depth information. Particular attention will be given to the design and modelling of both observation- and background-error covariances, which play a crucial role in spreading observational information to unobserved parts of the Earth system model. Different ways of distributing sea-ice and snow increments among the multi-category SI^3 model will be explored, following the recent study by Browne et al. (2025). A new balance relationship between sea-ice and ocean state variables needs to be considered with extended NEMOVAR balance operators. The treatment of analysis increments in edge cases, where the straightforward addition of the increment would have violated model assumptions or led to unphysical model states, will also be considered.

Development work will first be carried out in the framework of the ECMWF ocean–sea-ice reanalysis system, ORAS6. ORAS6 uses flow-dependent background-error covariances via a hybrid ensemble-variational configuration of NEMOVAR (see Chrust et al., 2024). We will need to revisit our ensemble generation methods in light of the new cryospheric variables modelled and assimilated. Ensemble spread of sea-ice background states will be evaluated for the optimised configuration of the EDA system. New methods like stochastic perturbation of sea-ice variables will be investigated, if necessary. After making all these improvements to NEMOVAR, we will test the performance of ECMWF's outer-loop-coupled DA system (de Rosnay et al., 2022) when this version of NEMOVAR is used in the ocean and sea-ice components of the coupled system.

As discussed in the Section 3.2, ECMWF does not yet have the capability to assimilate L1b CRISTAL-like data, which are waveform parameters of altimeter range data. Additional auxiliary input data from other sources are needed to convert L1b data into geophysical parameters such as sea-ice freeboard and snow depth. A series of geophysical corrections are needed to generate CRISTAL-like L2 products, including dry and wet tropospheric corrections, high-frequency atmospheric correction, ionospheric correction and various ocean and earth/polar tide corrections. While some of these geophysical corrections (e.g. dry tropospheric correction and high-frequency atmospheric correction) can be potentially included in the forward model by using ECMWF's IFS forecasts, tide corrections will still pose a challenge because no ocean tide model has been implemented in the ECMWF system. On the other hand, forward models for grid-box-averaged values of sea-ice freeboard and snow depth data are already in place in the ECMWF system. Therefore, instead of assimilating L1 CRISTAL-like data, we propose to focus on the assimilation of CRISTAL-like sea-ice freeboard and snow depth data within DANTEX, as discussed in the DANTEX kick-off meeting on 18 November 2024. This proposed change is also reflected in the roadmap for achieving the DANTEX project objectives (see Section 6.1.2).

In the future, we can explore direct assimilation of CRISTAL-like L1b data by taking a similar approach as described in Semane et al. (2024). This approach allows assimilation of L1b altimeter range data without correction of atmosphere delay (e.g. high-frequency atmospheric correction) by simultaneously adjusting both the atmospheric state and sea-surface height at the measurement location. This will require development of additional forward-model capabilities within the ECMWF outer-loop-coupled DA system, including the introduction of ocean-tide modelling in the ECMWF system. Development of a new observation operator is also needed. However, it is recognised that this part of the development work is beyond the scope of the current phase of the DANTEX project.

5. Description of datasets to be used during the testing phase

To test CIMR-like data in the ECMWF system, AMSR2 provides most of the frequencies observed by CIMR and observes at a similar zenith angle, but it has approximately two to three times larger footprints. However, the microwave imager data are currently superobbed[3] to a 40 km resolution, so this is not a major problem outside coastlines and the sea-ice edge (further discussion on this can be found in Section 6.1.1). ECMWF has an archive of AMSR2 data from 2012 onwards, which will support our requirements in providing CIMR-like data at 6.9 GHz and above.

For testing CIMR-like measurements at L-band, SMOS and SMAP are both available in the ECMWF observational data archive (from 2009 and 2020 respectively). SMOS observes at a range of zenith angles from nadir to around 60°, whereas SMAP observes at a fixed zenith angle of 40°. CIMR will have a fixed zenith angle of around 55°, but slightly lower at approximately 52° for L-band. Given the difficulty of handling multiple zenith angles from SMOS and the complex viewing geometry more generally, it is preferred that SMAP data be used. The difference in sea-ice emission properties between 40° and 55° is not that large, though any empirical modelling components developed for SMAP will

[3] Superobbing and superobbed are conventionally used verb forms that refer to the creation of super-observations (averages of observations over a specified area).

need to be re-trained on CIMR data when they are available, to provide exactly the right characteristics for the 55° zenith angle. SMAP is also preferred due to its higher resilience to RFI compared to SMOS (Piepmeyer et al., 2014). Therefore SMAP will provide the required L-band data in this project.

For testing CRISTAL-like SIT freeboard and snow depth measurements, a proxy dataset will be provided by ESA (via the Copernicus Expansion Mission Product Algorithm Laboratory (CEM-PAL)). This simulated CRISTAL dataset will include CryoSat-2 and/or Sentinel-3 measurements in a CRISTAL-like format. We can also use the existing CRISTAL-like sea-ice freeboard data from CryoSat-2, ICESat-2, Sentinel-3 and AltiKa to carry out technical testing with the newly developed ECMWF system.

6. Roadmap to achieve the identified objectives in terms of development and testing

In this section, we outline the work planned as part of the current phase of DANTEX. The developments will be performed with a focus on the cryosphere, with the developments for both CIMR- and CRISTAL-like data to be fed into the same coupled DA system. The work is organised in two main phases: the development and testing phase (Work Package (WP) 2.1), and the validation and assessment phase (WP3.1). For CIMR-like data, most of the developments will be performed or integrated inside the atmospheric 4D-Var system, whereas for CRISTAL-like data, the focus will initially be on the ORAS6 system. The work during the development phase of WP2.1 will hence be described separately for the two instruments. During the validation and assessment phase in WP3.1, these developments will be brought together, and the impact of the developments will be evaluated both jointly and separately. Evaluation of synergies between the two instruments is an important aspect of this assessment.

The timings given in the roadmap below are consistent with those given in the proposal, with an adjusted start date of DANTEX of 1 December 2024. This is to account for the start dates of newly recruited DANTEX-funded staff and to nevertheless keep DANTEX reporting and developments for different instruments in step with each other. An overview of the different tasks to be performed is given in Figure 2. Requirement (REQ) numbers quoted throughout this section are taken from the DANTEX Statement of Work document appended to the project contract.

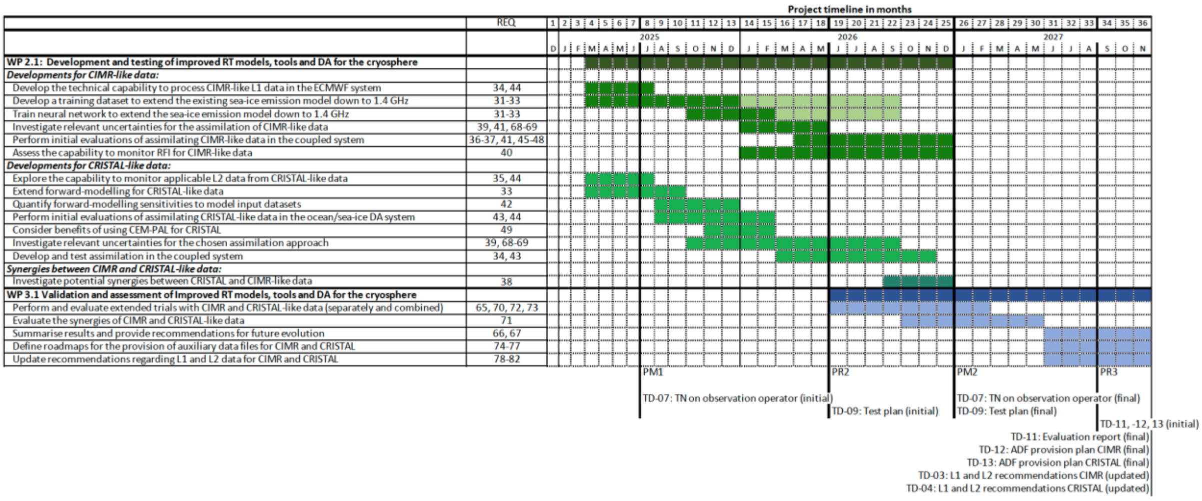

Figure 2: Gantt chart of the work to be performed for the cryosphere in preparation of using CIMR and CRISTAL data. See the main text for further details. The start date for DANTEX is taken to be 1 December 2024.

6.1 WP 2.1: Development and testing of improved RT models, tools and DA for the cryosphere (1 March 2025 to 31 December 2026)

6.1.1 CIMR

The assimilation of CIMR data will be prepared by using a combination of SMAP and AMSR2 observations to develop the required forward modelling and assimilation capabilities in ECMWF's coupled DA system.

Develop the technical capability to process CIMR-like L1 data in the ECMWF system [REQ-034, 044] (by 31 July 2025)

The technical framework will be developed to process SMAP observations in the all-sky microwave framework within ECMWF's atmospheric DA component, to complement the already existing processing of AMSR2 data. This includes developments in the pre-processing stage, where the observations will be superobbed to 40 km resolution following the treatment of existing sensors like AMSR2. This resolution is broadly consistent with the SMAP and CIMR L-band footprint size and slightly smaller than that of the AMSR2 6 GHz and 7 GHz channels. In situations where the sea ice is a field of continuously varying concentration, any resulting errors from a larger footprint are likely to be small. However, where the ice forms sharp edges and features, and in the vicinity of coastlines, the deactivation of these channels may be needed. For these technical developments, the forward modelling over sea ice will use the existing "v2" sea-ice emissivity model, either by allowing the neural network to extrapolate down to 1.4 GHz or using the 10 GHz values for all lower frequencies, depending on which option provides the best results. The successful output of this phase will be maps of background departures over sea ice for SMAP and the 6/7 GHz channels of AMSR2. As the sea-ice emissivity model used has not been optimised for these frequencies, these departures may have large errors over sea ice. At this stage, the new observations will not be actively assimilated but only passively monitored. Active assimilation developments are the subject of later work.

Develop a training dataset to extend the existing sea-ice emission model down to 1.4 GHz [REQ-031, 032, 033] (initial one-year dataset by 31 December 2025; final, potentially extended dataset by 30 September 2026)

Training datasets will be developed to extend the empirical sea-ice emissivity framework down to 1.4 GHz. The training datasets combine observations from relevant instruments with output from the IFS, run at a suitably chosen resolution over a minimum of one year. They will use an internal ECMWF data format, referred to as Observation Database (ODB). The dataset preparation follows Geer (2024a), with additional developments as follows:

- Using ECMWF's coupled system, we shall save the available sea-ice and snow model parameters from the SI^3 sea-ice model at observation locations. This aims to provide information on the bulk temperature, thickness, density or mass, salinity and humidity (liquid water content) of the ice and snow layers, as represented in the forecast model (either from SI^3 or the multi-layer snow model on sea ice from the atmospheric model), plus any additional available information on the microstructure if available. Initially, these parameters will be of great benefit in understanding the performance of the sea-ice emissivity model in different regimes, but in the future they may be used as inputs into a more generalised sea-ice RT model. The outcome of this task is to generate a few days of AMSR2-based data augmented with sea-ice and snow parameters, and to compare these parameters to the simulated snow-surface emissivity to check for geophysical consistency.

- Once SMAP is supported in the ECMWF DA system (see above), we shall generate a training dataset for one year covering the sensors SMAP, AMSR2, SSMIS and GMI, to provide an initial training database for the sea-ice surface emissivity model.

- The training dataset may be extended once a suitable approach to adapt the sea-ice surface emissivity model has been developed (see below), in order to cover a greater variety of surface conditions of sea ice (including, e.g., years with greater and less SIE). The resulting training dataset will be used to create the final version of the updated sea-ice surface emissivity model. It should also support future developments, either during a future phase of DANTEX or outside the DANTEX project.

Train a neural network model to extend the sea-ice emissivity model down to 1.4 GHz [REQ-031, 032, 033] (v3a by 28 February 2026; v3b by 30 September 2026)

Forward modelling capabilities suitable for CIMR will be developed by extending the existing empirical "v2" sea-ice emissivity model using the above-developed training datasets. The existing multi-instrument training uses AMSR2, SSMIS and GMI at 10 GHz and upwards. The training process will be extended to include 1.4 GHz data from SMAP and 6/7 GHz channels from AMSR2. The resulting new model "v3" will be simultaneously capable of simulating an effective sea-ice surface emissivity at observed frequencies between 1.4 GHz and 183 GHz, and therefore capable of supporting all currently operational conically scanning microwave radiometers at the chosen, fixed zenith angles. We will experiment with training the neural network model from scratch or using the existing v2 model as the starting point for training, a process known as transfer learning. The model will be trained in two main phases:

- v3a, based on the initial single year of training data, represents a prototype that can be used in the IFS. It allows further development of the DA system for SMAP and AMSR2 6/7 GHz.
- v3b is based on the final, potentially extended training dataset. It will be used in the final experiments during 2026.

Investigate relevant uncertainties for the assimilation of CIMR-like data, including errors of representation, by considering observation-monitoring statistics, and adapt assimilation approaches accordingly [REQ-039, 041, 068, 069] (by 31 May 2026)

In order to set up the IFS for assimilation of SMAP and the 6/7 GHz channels of AMSR2 in sea-ice areas, it is necessary to evaluate the size and extent of any biases, along with the total random error (e.g. the standard deviation of the background departures). This will be done using observation-minus-background (O-B) departures over one year of passive monitoring using the v3a surface emissivity model for SMAP and the 6/7 GHz channels of AMSR2. The DA settings will then be adjusted accordingly:

- Observation-error settings will be guided by the O-B standard deviation, with the possibility of state-dependent variations in this error.
- The O-B mean will be examined, both on a monthly basis and as far as possible by local solar time, for areas where systematically large and non-zero departures are seen. These areas indicate poor performance of the forward model or systematic errors in the underlying model state. If they are particularly large, the DA will likely be unsuccessful in these areas, and quality control measures can be put in place to exclude such observations. Also, the systematic errors are helpful to guide future improvements in forward modelling.

Perform initial evaluations of assimilating CIMR-like data in the coupled system, considering all channels and vertical (V) and horizontal (H) polarisations as applicable [REQ-036, 037, 041, 045-048] (by 31 August 2026; with refinements by 31 December 2026)

Once the initial framework is in place in the IFS (namely, the v3a surface emissivity model, the capability to assimilate SMAP and the 6/7 GHz channels of AMSR2 over sea ice, and the initial observation-error and quality-control strategies as devised above), it is possible to run short DA experiments in the coupled DA system to evaluate the initial impact on the resulting analyses and forecasts, both for sea ice as well as the atmosphere, and to identify areas where updates and improvements are required. These will be used to refine assimilation approaches for CIMR-like data.

Deliverables:

- TD-07: Technical note on the observation Operator (REQ-047)
- SW-01: Observation Operator software as open-source (REQ-045, 046)
- TD-09: Test plan to validate the developments performed in the Work Package (REQ-048)

Assess the capability to monitor RFI for CIMR-like data using differences between observations and model-equivalents, or provide flagging for relevant areas [REQ-040] (by 31 December 2026)

The examination of O-B departures for RFI will follow the study by Scanlon et al. (2024) on evaluating RFI at 6 GHz to 10 GHz from AMSR2 over open ocean, with extension down to 1.4 GHz over sea-ice areas. The CIMR RFI flagging can only be evaluated on paper by assessing the results of past RFI flagging strategies.

6.1.2 CRISTAL

ECMWF will develop the capability to assimilate CRISTAL-like data in ECMWF's DA systems. Work will start with the development of an observation operator and DA capabilities within ORAS6 by using CRISTAL-like datasets (e.g. CryoSat-2, ICESat-2, Sentinel-3 and AltiKa). The assimilation of CRISTAL-like data in ECMWF's coupled DA system will then be explored to investigate potential synergies between CRISTAL and CIMR observations with a focus on the cryosphere.

Explore the capability to monitor applicable L2 data from a CRISTAL-like dataset [REQ-035, 044] (by 31 July 2025)

We will add infrastructure to the ECMWF DA system to passively monitor sea-ice freeboard and snow-depth observations from existing L2 altimetry products (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa) year-round, subject to data availability. The technical framework, including data acquisition and the pre-processing chain (e.g. quality control, thinning and/or superobbing procedures) for existing L2 altimetry products, will be implemented in ORAS6.

Extend forward-modelling capabilities (observation operators) to enable assimilation for existing CRISTAL-like data targeted at snow depth and sea ice (thickness, extent and concentration) [REQ-033] (by 30 September 2025)

We will develop an observation operator within ORAS6 for the passive monitoring of freeboard data and snow depth from CRISTAL-like datasets (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa). The observation operator code will be generic enough to cover both laser altimeter (ICESat-2) and radar altimeter (e.g. CryoSat-2) cases.

Quantify forward-modelling sensitivities to model input datasets, including input datasets from CryoSat-2, Sentinel-3, AltiKa [REQ-042] (by 31 December 2025)

We will test the newly developed observation operator for sea-ice freeboard and snow depth on various CRISTAL-like datasets (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa). Experiments will be carried out to evaluate and quantify the sensitivity of the observation operator to different input L2 altimetry products by treating them as passive observations. This will be guided by observation-space diagnostics such as O-B statistics.

Deliverables:

- TD-07: Technical note on the observation Operator (REQ-047)
- SW-01: Observation Operator software as open-source (REQ-045, 046)

Perform initial evaluations of the potential utility of assimilating CRISTAL-like data [REQ-043, 044] (by 28 February 2026)

We will develop a simple DA scheme (e.g. uni-variate) for the assimilation of CRISTAL-like (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa) sea-ice freeboard data in ORAS6, and evaluate the potential impacts of assimilating such data with a focus on the cryosphere.

Consider the benefits of using CEM-PAL to produce test datasets to be used as input for CRISTAL validation and assessment activities [REQ-049] (by 28 February 2026)

For the technical development of assimilating CRISTAL-like sea-ice freeboard data, existing datasets (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa) would be sufficient. Yet, test datasets from CEM-PAL will be useful because they will be in a CRISTAL-like format, with co-located measurements of sea-ice freeboard and snow depth. Such datasets can be used for validation of developments that will be performed in this work package.

To enable this activity to complete in time (by 28 February 2026), we will need the CEM-PAL test datasets from ESA by the start of November 2025. Such test datasets should, as far as possible, satisfy our data requirements as outlined in the TD-04 document.

Deliverable:

- TD-09: Test plan to validate the developments performed in the Work Package (REQ-048)

Investigate relevant uncertainties for the assimilation of CRISTAL-like data, including errors of representation, by considering observation-monitoring statistics, and adapt assimilation approaches accordingly [REQ-039, 068, 069] (by 30 September 2026)

On the observations' side, we will develop a linearised version of the sea-ice freeboard observation operator and its adjoint code to be used in NEMOVAR. We will also develop and test a new observation error model and observation perturbation system for sea-ice freeboard observations to accurately represent uncertainty in an EDA.

On the other hand, in terms of background-error modelling, we will adapt the sea-ice DA system currently developed by Browne et al. (2025) to extend the control vector for enabling the assimilation of sea-ice freeboard data. The following control variables will be considered:

- Multi-category SIC control variables
- SIT control variables
- Sea-ice volume control variables

Next, we will develop a cross-covariance model between the new control variable and other control variables within NEMOVAR. The background-error model will be constructed by using either a balance operator or following a diffusion approach, similar to the current NEMOVAR system (see Weaver et al., 2005; Mogensen et al., 2012). Various ways of building the balance relationship will be explored to test the sensitivity to different errors of representation in the assimilation of sea-ice freeboard data.

Observation-monitoring statistics (such as O-B) will be used to guide the assessment of effectiveness and efficiency of the above-mentioned developments.

Finally, we will carry out experiments to assimilate CRISTAL-like sea-ice freeboard data with the newly developed observation-error and background-error models in ORAS6 for final evaluation.

If time permits, we will extend the development work mentioned here to include snow-depth observations in addition to sea-ice freeboard.

Develop the assimilation of CRISTAL-like data in ECMWF's coupled system, with a focus on the cryosphere [REQ-034, 043] (by 30 November 2026)

Having tested the assimilation of CRISTAL-like (CryoSat-2, ICESat-2, Sentinel-3 and AltiKa) sea-ice freeboard data in ORAS6, we will perform similar tests on our outer-loop-coupled DA system to assess the impacts of sea-ice freeboard DA in the atmosphere. Performance in the cryosphere (especially the Arctic region) will remain to be the focus.

6.1.3 CIMR and CRISTAL combined

Investigate potential synergies between and CIMR- and CRISTAL-like data in the assimilation system [REQ-038] (by 31 December 2026)

Once the CRISTAL and CIMR prototype DA systems are available, they can be evaluated in combination in the ECMWF coupled DA system. Observing system experiments (OSEs) will be carried out to enable an evaluation of how the different strengths of these instruments can be combined to give an improved sea-ice representation and improved forecasts.

6.2 WP 3.1: Validation and assessment of updated RT models, tools and DA for the cryosphere (1 June 2026 to 30 November 2027)

This work package brings together the DA frameworks developed for CIMR and CRISTAL-like data in WP2.1 and evaluates the new DA capabilities over extended periods. Periods used for testing will cover both ice freeze-up and break-up periods for both hemispheres, with a minimum of two three-month periods. The work package will also provide further recommendations for the design of data products and further developments for CIMR and CRISTAL based on the lessons learnt from the present study. The following aspects will be done:

Perform and evaluate extended trials with CIMR- and CRISTAL-like data, separately and combined (by 28 February 2027)

We will carry out extended assimilation trials with CIMR- and CRISTAL-like data in ECMWF's coupled DA system and evaluate the performance. These will be performed in the form of OSEs, in which CIMR- and CRISTAL-like data are added to a system without such data, both separately and combined. For CRISTAL-like data, a particular focus will be on the chosen Earth-system approach (ocean–sea-ice DA or coupled DA). This work will address REQ-065, 070, 072 and 073.

If needed, the Observation Operator code (SW-01) and related technical notes (TD-07) will be updated [REQ-082].

Evaluate synergies between CIMR- and CRISTAL-like data [REQ-071] (by 31 May 2027)

We will evaluate synergies between CIMR- and CRISTAL-like data by performing assimilation experiments in which the data are used separately as well as in combination. The complementarity of the two observation datasets will be investigated, with a particular focus on the cryosphere.

Summarise results and report recommendations (by 30 November 2027)

We will summarise the results of this work package and provide recommendations for future evolution of the DANTEX project [REQ-066, 067]. In addition, we will define a roadmap for the provision of auxiliary data files (ADF) required for the operational phase of CIMR and CRISTAL, taking into account the Algorithm Theoretical Basis Documents (ATBDs) provided by ESA, the ESA format specifications, mission requirements and the evaluation results [REQ-074, 075, 076, 077]. We will also provide recommendations for future developments regarding data products and their applications, and will discuss relevant aspects such as ADFs, mission requirements, product quality and further exploitation of CIMR and CRISTAL data in the TD-03 and TD-04 reports [REQ-078, 079, 080, 081].

Deliverables:

- TD-11: Evaluation report
- TD-12: ADF provision plan
- TD-13: ADF provision plan
- TD-03: Recommendations on the design of CIMR data products (updated)
- TD-04: Recommendations on the design of CRISTAL data products (updated)

7. Definition of metrics for the performance assessment of improved models and tools

The primary metric of improved performance of a coupled forecasting system is given by the quality of atmospheric, oceanic and sea-ice forecasts. For example, an improved description of sea ice is expected to improve weather forecasts through an improved representation of heat, moisture and momentum fluxes between the ocean/sea-ice and atmosphere. Changes in these areas are expected to affect temperature and wind forecasts in the medium range (up to 10 days ahead). Changes in forecast quality will be measured in the usual way, both against analysed fields and against the full atmospheric, oceanic and surface observing system. For the latter, we will assess changes in the fit between a short-range (12-hour) forecast and observations, hence providing indirect assessments against the full global observing system. Performance will be assessed using maps, time series, pressure-latitude diagrams, as well as scorecards against analysis and observations.

Given the lack of in-situ data on sea ice and the limited geographical regions that are covered by sea-ice observations (primarily the Arctic), we do not expect to make much use of in-situ observations of sea ice in this project. Such observations are limited to campaign data with confined geographical and temporal coverage. They include the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Nicolaus et al., 2022), which broadly follows one ship embedded in sea ice for a year and provides highly detailed research measurements, and Operation IceBridge, which was based on a number of aircraft over-passes using remote sensing (Kurtz et al., 2013). While these observations are informative for detailed process studies and cryosphere research, their use for evaluating global analyses and forecasts of sea ice is very limited. Problems include the very limited sampling of the globe and the northern-hemisphere focus, thus making the results likely unrepresentative. Also, the highly heterogenous nature of typical campaign data (different instruments and teams; non-standard formats and archiving) makes it highly labour-intensive to use such observations. For SIC specifically, the problems of validating satellite data are well illustrated by Kern et al. (2019). They note significant issues with ship-borne datasets, including the limited number of voyages in any year, the variable quality of SIC estimates made by human observers under different weather and illumination conditions, and sampling errors due to ships' tendency to avoid thick and continuous sea-ice cover. For these reasons, we will not include comparisons against such observations in evaluating our developments.

Similarly, although satellite retrievals of SIC and SIT exist, we will already be making use of those relevant observations within the DA system. Hence, although comparison of the new ECMWF SIC and SIT analyses against the retrieved observations can provide useful information, it cannot be used as a metric of performance. Yet, to ensure that the DA system is using the information from CIMR- and CRISTAL-like observations properly, we can use DA consistency requirements to evaluate our experiments. For example, we would like to see analysis departures being smaller on average than background departures, which indicates that observational information has been incorporated in the analysis.

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