ARKTALAS HOAVVA PROJECT

DELIVERABLE 160: SCIENTIFIC ROADMAP

Customer	ESA
Author	Consortium
Distribution	Consortium and ESA
ESA Contract Number	4000127401/19/NL/LF
Document Reference	Deliverable D-160
SoW Deliverable Reference	
Version/Revision	1.0
Date of issue	9. October 2023

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Revision Change log

Issue	Date	Type	Change description
1.0	9. October 2023	Submitted to ESA	

The Arktalas Scientific Roadmap (SR) shall build on the outputs, lessons learned, knowledge, international collaboration, and tools developed by the project showing how the outcomes of the study could translate into future activities. The SR shall in particular:

- *i. Articulate all lessons learned during the project;*
- *ii. Identify priority areas to be addressed in potential future activities;*
- *iii. Any other aspect assisting ESA in the development of future scientific activities related to the Arctic Ocean.*

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1 INTRODUCTION

In the high latitude seas and Arctic Ocean, global warming and Arctic Amplification are considered to occur across a range of environmental state variables with complex interactions and feedback mechanisms at regional to global scales (Bojinski et al., 2014, Lavergne et al., 2022). Central among these are changes in the radiation balance, changes in ocean-sea ice-atmosphere momentum, heat and gas exchanges, reduction in the sea ice extent and thickness, and changes in the bio-optical properties in the upper ocean. In turn, the Arctic Polar Regions experience increased air temperature, delayed onset of sea ice freezing, early onset of sea ice melting, increasing area of melt ponds, polynyas and surface meltwater, increased lead fraction and sea ice drift, reduction of near shore fast ice area, changes of snow cover, snow water equivalent (SWE), changes in albedo, a much larger wind fetch and enhanced wave-sea ice interaction leading to sea ice break-up and delays in freeze-up , as well as shifts in and expansions of the Marginal Ice Zone (MIZ). Moreover, the atmospheric boundary layer adjustment to these changes is anticipated to alter the weather patterns and influence the Arctic vortex, with corresponding atmospheric teleconnection to lower latitudes.

In the Arktalas Hoavva project, four major interlinked Arctic Scientific Challenges (ASC) have been investigated with the goals to:

- Characterize the Arctic Amplification and its impact (ASC-1)
- Characterize the impact of more persistent and larger area of open water on sea ice dynamics (ASC-2)
- Characterize and predict the impact of extreme event storms on sea-ice formation pattern and structures (ASC-3)
- Characterize and predict the Arctic Ocean spin-up (ASC-4)

The investigation has been executed across seven interlinked specific objectives, including:

- **OBJ-1:** Define and implement scientific analysis, with a focus on synergy application building on a multi-modal data-driven analyses framework.
- **OBJ-2:** Develop and generate a multi-mission database of satellite, model outputs and in-situ measurements for the Arctic Ocean over a period of at least 10+ year including the implementation of a data access system and data visualisation and scientific analysis tool.
- **OBJ-3:** Undertake at least 6 science driven case studies addressing the Arktalas Scientific Challenges.
- **OBJ-4:** Analyse the impact of planned future missions on Arktalas Scientific Challenges with a focus on their likely impacts and contribution to synergic application of EO data sets.
- **OBJ-5:** Prepare and submit 7 scientific journal articles reporting the scientific outcomes of the Arktalas study.
- **OBJ-6:** Prepare a Scientific Roadmap of potential future activities and collaborations.
- **OBJ-7:** Promote the Arktalas study and application of ESA satellite missions in the Arctic Ocean.

In line with these 7 objectives the Arktalas Hoavva project approach has been executed through the following 9 major tasks:

- **Task 1:** Preparation and planning of the data collection and corresponding scientific analyses ***(OBJ-1);***
- **Task 2a:** Arktalas Hoavva data collection and quality control ***(OBJ-2);***
- **Task 2b:** Implementation of analyses and visualization system ***(OBJ-2);***
- **Task 3:** Scientific analyses of the Arktalas Hoavva data set ***(OBJ-3 and OBJ-5);***

- **Task 4:** Analyses of future satellite mission impacts in understanding the changes to the Arctic Ocean ***(OBJ-4 and OBJ-5)****;*
- **Task 5:** Promotion of the Arktalas Hoavva study and scientific community outreach ***(OBJ-7)****;*
- **Task 6a:** Creating a scientific roadmap ***(OBJ-6)****;*
- **Task 6b:** Final report ***(OBJ-6);***
- **Task 7:** Arktalas Hoavva Project Management

As indicated these tasks have clear links to the 7 specific objectives. They are also strongly interconnected as illustrated in the work-breakdown lay-out shown in Figure 1.

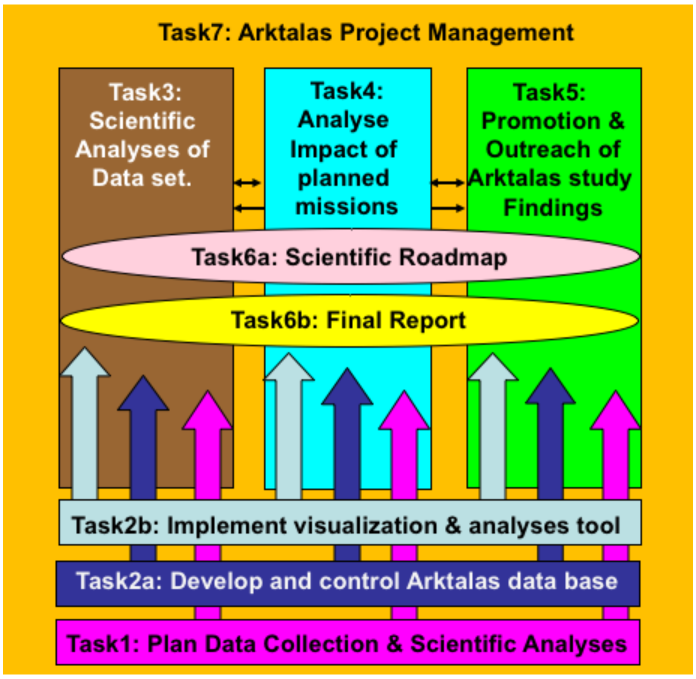

Figure 1. *Schematic outline of the Arktalas Hoavva work breakdown and approach*

The Arktalas Scientific Roadmap deliverable capitalizes on the major findings and results, new knowledge, lessons learned and tools developed in the project. In parallel and in relation to this, new questions and identification of challenges have emerged. The Scientific Roadmap outline how these are translated into recommendation of opportunities and activities that may assist ESA in the selection of future scientific activities related to multi-disciplinary Earth observations of the Arctic Ocean and the surrounding neighbouring seas. The major findings are highlighted in Section 2, followed by lessons learned in Section 3 and the Summary and Recommendation in Section 4.

2 MAJOR FINDINGS

The Arktalas Hoavva project adopted a stepwise multi-modal analyses framework approach to address the four major Arctic Scientific Challenges. This approach benefits from multiscale resolution satellite observations together with complementary in-situ data, computer model simulations, data assimilation, analyses, and integrated visualization tools. The major findings and results that emerged from the corresponding 7 scientific research papers are highlighted below.

Esau et al., (2023) have reviewed and assessed how the remote sensing data, and particularly climate products, have captured signals of the Arctic Amplification such as the rapid and massive transition from multiyear to seasonal sea ice, and from tundra to tall shrubs and forest. The Arctic Amplification of surface temperature has been observed to come in pulses. Long periods of high internal climate variability and slow climate trends are followed by intense decades of rapid and considerable changes. The most recent such periods have been captured by a multitude of satellite observations.

The traditional paradigm put the weight on local climate processes and feedbacks, such as, e.g., the ice-albedo feedback. However, a new paradigm attributes the Amplification drivers to the global energy sink and source redistribution, and therefore to dynamic effects in the atmospheric and oceanic meridional circulation. The local feedbacks are following in this paradigm making the Amplification apparent in the surface changes such as in the recent rapid temperature raise at the Barents Sea northern margins. Decades ago the multiyear sea ice kept both the surface air temperature and the sea surface temperature at melting point during summer, thus, inhibiting heat accumulation and related surface-layer feedbacks. In 2000s, on the other hand, multiyear ice has largely retreated and the solar heating has got access to the upper ocean storage reservoir triggering further warming and setting back winter ice formation. In addition, as land cover is more responsive to heat inflow in the atmosphere, Arctic vegetation productivity began to increase earlier with dominant effect of tundra shrubification and afforestation.

Regan et al. (2020) have explored the impact of increased temperatures in the Arctic (manifested through the Arctic Amplification) on the basin scale atmospheric and ocean circulation using altimetry-based datasets together with a high-resolution eddy-resolving model with focus on the Beaufort gyre over the period 1990-2014.

The Beaufort Gyre is an anticyclonic upper-ocean circulation feature that is the largest reservoir of fresh- water in the Arctic Ocean. The gyre has spun up over the past two decades in response to changes of the wind forcing and sea ice conditions, accumulating a significant amount of freshwater. This has an impact on the circulation in the Arctic Ocean as well as the variability of freshwater export from the Arctic, which again has the potential to influence the North Atlantic circulation and climate affecting the deep-water formation and global conveyor belt circulation. The simulation performed with a high-resolution, eddy-resolving model reveals the spatial-temporal evolutions of the mean and eddy kinetic energy in the Canada Basin with a higher level of mean kinetic energy that is generally not accompanied by higher levels of eddy kinetic energy. On average the levels of mean and eddy kinetic energy are of the same order of magnitude, with the eddy kinetic energy only intensified along the boundary and in the subsurface. In response to the strong anomalous atmospheric conditions in 2007, the gyre spins up and the mean kinetic energy almost doubles, while the eddy kinetic energy does not increase significantly for a long time period. This is because the isopycnals are able to flatten and the gyre expands outwards, reducing the potential for baroclinic instability. All in all, the results have implications for understanding the mechanisms at play for equilibrating the Beaufort Gyre and the variability and future changes of the Arctic Ocean freshwater system and its export to the global oceans through the Fram Strait, Canadian Archipelago and Bering Strait.

***Rheinlaender et al. (2022*)** have investigated whether the thinning of sea ice and enhanced areas of open water in the Arctic Ocean may be more effectively exposed to extreme events. A distinct large sea-ice breakup event in the Beaufort Sea in response to a series of storms encountered in February–March 2013 formed the baseline for the study. The novel sea ice model - neXtSIM invoked with sea ice thickness derived from Cryosat-SMOS was used to simulate this storm-induced breakup. In comparison to lead detections obtained from MODIS the model has shown promising capabilities to reproduce the timing, location, and propagation of sea-ice leads associated with the breakup event.

Sea ice breakup events may furthermore have a large effect on local heat and moisture transfer and cause enhanced sea ice production, but also increased sea ice drift. Moreover, a complementary question is whether the changes in the sea ice extent and thickness will favour increasing frequency and strength of extreme events. These extreme sea ice breakup events are generally not captured by climate models and may thus potentially limit the accuracy in projections of future Arctic sea ice conditions.

Cassianides et al. (2020) have developed a promising new method to detect ocean eddies in SAR images of the sea ice field. While evidence of mesoscale eddies expressed in the sea ice field has been impeded by the presence of compact sea ice concentration in the past, the recent decline in sea ice concentration and extent allow for clearer expressions of mesoscale features in the sea ice field.

By combining directly observed upper ocean currents under the sea ice in the Beaufort Gyre Exploration Project, the expression of ocean surface eddies revealed in the sea ice vorticity field have been derived from analysis of high-resolution images SAR data. Through processing of pairs of SAR images the sea ice drift is estimated by combining feature tracking and pattern matching techniques. Combining two or more images the sea ice vorticity are then calculated over several time periods, to evaluate the persistence of the signal.

Collard et al. (2022) have applied an innovative sensor synergy combination of data from ICESat-2, Sentinel-2, Sentinel-1, Sentinel-3 Fully-Focused SAR altimetry and CFOSAT-SWIM to detect wave patterns in the sea ice field. These multi-sensor observations are highly important to advance the understanding of interactions of waves and sea ice with possible consequences for sea ice cover breakup.

A consistent quantitative interpretation of ICESat-2 and Sentinel-2 data is made on waves generated by storms in the Barents Sea that are observed to travel hundreds of kilometers across the marginal ice zone and into the pack ice. The use of multi senor data strongly expand the quantity of available wave information for scientific investigations and operational applications in the polar oceans. This clearly advocates for a synergetic approach, building co-located datasets to achieve better quantitative understanding of the propagation and interactions of waves and sea ice. The quantification of wave heights, on the other hand, are still subject to validation.

Boutin et al. (2021) have evaluated the ability of wave-in-ice models at the scale of the Arctic Ocean and over periods longer than a few days with the goal to explore how far waves can propagate into the sea ice field.

The study makes use of the wave-affected fraction dataset from ICESat-2 to assess the ability of a coupled wave—sea ice model to capture the extent to which the waves propagate into the sea ice field. The comparison is not straightforward as model and observations data are very different. Moreover, the observations are also sparse and only detect waves above a certain wave height. All in all, the simulated wave propagation agrees well with observations, especially in winter. In autumn, on the other hand, the model underestimates the area affected by waves in the western part of the Arctic Basin. The study clearly highlights the need for wave-in-ice models to maintain strong wave attenuation in thick, compact ice, whereas weaker attenuation are preferable in summer or during sea ice formation periods. Improved quality of wave-in-sea ice modelling will, in turn, lead to better understanding of wave-sea ice interactions and estimation of wave-induced sea ice breakup. It will also enable better assessment of the impact of a more persistent and larger area of open water on sea ice dynamics in a future Artic Ocean.

Cancet et al. (2023) have investigated the impact of sea ice change on ocean tides in the Arctic Ocean, considering model simulations and observations from satellite altimetry and tide gauges. Although ocean tides are one of the major contributors to the energy dissipation in the Arctic Ocean, their characteristics are far from fully known. In particular, the interactions between tides, the sea-ice, grounded-ice and fast-ice cover are often simply ignored in tidal modelling simulations or considered through relatively simple combinations with the bottom friction.

Moreover, they also highlight the fact that most of the past and present altimetry missions that reach high latitudes are sun-synchronous. This strongly limits their capability to observe part of the ocean tidal cycles. However, thanks to the higher density of ground tracks in high latitude regions, it is possible to bin the altimetry measurements to reconstruct time series with finer time sampling and consequently reduce the tidal aliasing effects. A mission like CryoSat-2, for instance, has brought remarkable measurements to improve the tidal estimates in the Arctic Ocean, thanks both to its SAR along track and SAR-interferometric modes that enable more accurate SSH estimations in sea-ice covered coastal regions. In addition, the non-sun-synchronous orbit offer more reliable recovery of the major tidal components in contrast to the aliased signals retrieved in sun-synchronous orbits. As such, a long observational gap between the CryoSat-2 and CRISTAL missions may have serious impact on the quality of the tidal retrievals. In turn, this will hamper the uncertainty estimates from tidal models of the Arctic Ocean, which are used to remove the ocean tide signals from the altimeter SSH measurements to build the climate products.

Lucas et al. (2023) addressed how the satellite-based continuity and new approved missions (Figure 2) are expected to advance the understanding of the air - sea ice - ocean interactive processes in the Arctic Ocean and its marginal ice zones. The Sankey diagram evidences a broad and sustainable satellite-based observation capabilities of the key sea ice related variables with a promising outlook in the coming decade thanks to the addition of Explorer missions and Copernicus expansion missions. This will be increasingly important when human presence is expected to grow through increased shipping, fisheries and other activities in the Arctic Ocean and surrounding high latitude seas. By bringing new observations, often at higher spatial resolution, the approved future satellite missions will also contribute to improve the ability for model validation and assimilation in higher-resolution numerical models. In turn, this will contribute to better understanding of the complex processes in the Arctic Ocean and allow the revision and upgrade of the sea ice thermodynamics and rheology modelling approaches to better reproduce the complexity of the atmosphere - sea ice - ocean interactions and multiple feedback processes. In turn, more accurate simulations, re-analyses and reliable reconstruction of long time series can be expected, that are of prime importance to characterize an Arctic Ocean in transformation.

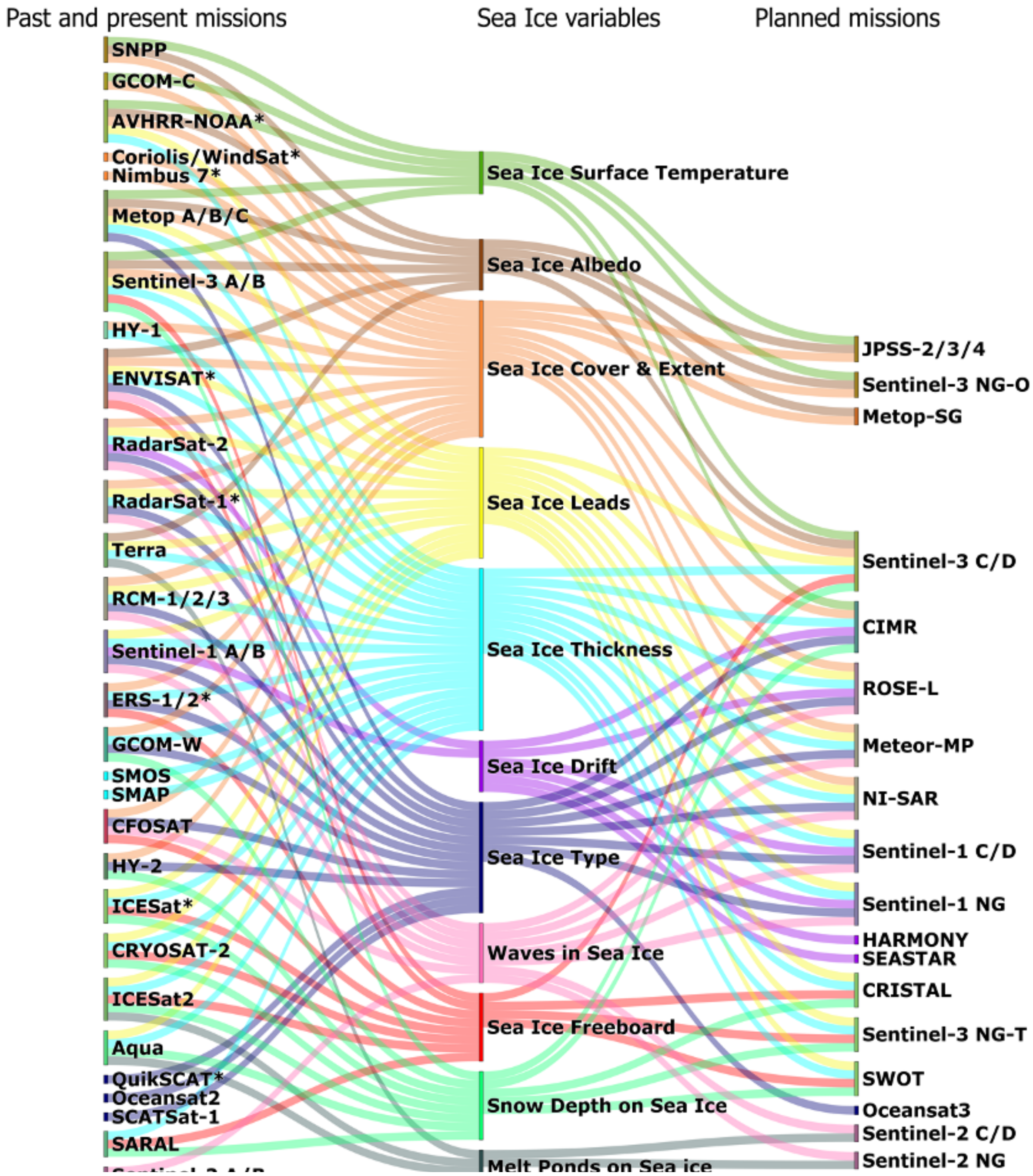

Figure 2. *Sankey diagram linking a subset of past, present and future approved satellite missions and their sea ice measurement capabilities. (left) Past (identified with *) and present satellite missions; (center) retrieved sea ice variables; (right) future approved missions.*

3 LESSONS LEARNED

In order to fully benefit from the satellite-based observation capabilities there is a crucial need for Fiducial Reference Measurement (FRM) data for calibration and validation, in particular as finer spatial resolution are emerging. Moreover, towards 2030 advances in development of Digital Arctic Twin components jointly with regular reprocessing, use of sensor synergy and multi-modal physical constrained co-variability analytics are likely to deliver more reliable estimates of sea ice drift, damage, break-up, lead fraction, new ice formation, sea ice freeboard height, sea ice volume, mean sea level and sea surface height. In turn, the quantitative understanding of the dominant multidisciplinary physical interactive processes that drive the sea ice thermodynamic state and variability in the Arctic Ocean and its marginal ice zones is anticipated to strengthen, notably regarding:

- atmospheric boundary layer stratification and thermodynamics;
- upper ocean stratification and thermodynamics;
- momentum, gas and heat fluxes;
- freshwater spreading;
- local and non-local connexions.

Indeed, the approach must advance better understandings of the role of the changing sea ice cover for the marine ecosystem, coastal erosion and the long-distance atmospheric teleconnection that, in turn, influences the weather and climate at mid-latitudes. As the sea ice cover breaks up, it exposes the underlying warmer ocean to the atmosphere within polynyas and narrow elongated openings in the sea ice cover known as leads. This has important consequences for air-sea momentum, heat and gas exchanges, mesoscale eddy generation and dynamics and sea ice production, in particular, during winter months when the heat fluxes over sea ice are generally low, the oceanic heat loss within polynyas and leads may cause local air surface temperature rise of more than 20°C. In turn, this enhances turbulent convection in the atmospheric boundary layer, possibly driving further breakup and sea ice production. The sea ice breakup in winter due to storm events combined with long-distance wave propagation also weaken the sea ice cover, potentially preconditioning the minimum sea ice extent in the subsequent summer (Babb et al., 2019), and thus create positive feedback to the Arctic amplification (Esau et al, 2023). Extreme sea ice breakup events, expected to increase due to global warming, are therefore of crucial importance for understanding the seasonal to long-term evolution and change of sea ice extent and volume, which, in turn, affects weather, ecosystems, and local communities in polar regions and beyond (Forbes et al., 2016; Rheinlaender et al., 2020). Moreover, sea ice thinning and gradually disappearance can increase upper ocean currents and intensify upper ocean turbulence, particularly over the continental shelf edge. In turn, this can enhance upward heat flux to the surface to further reduce sea ice thickness and cover, even during winter.

Satellite measurements in the Arctic are unique but may be influenced by several technical, observational, and environmental challenges related to orbit, instrument type, cross-calibration and retrieved variables. Although the converging ground tracks of polar orbiting satellites favours improved coverage, limited coverage across the true North Pole of the central Arctic Ocean leads to the Polar gaps. The use of optical satellite instruments is also limited due to the polar night and commonly harsh meteorological conditions including clouds and haze. Long-term optical satellite data products are therefore fragmented, likely leading to biases towards observations in clear sky conditions, with both potential seasonal and geographical variations. Interpolation and gap closure methods are thus always questionable as they rely on assumption that the statistics under clear sky and overcast are the same. Systematic comparisons and analysis of optical and high-resolution radar observations are still limited, but shall be considered to identify these statistical changes. Climate datasets like the ESA Climate Change Initiative (CCI) that today are facing limitations should benefit from these studies. Further note that radiative transfer models are incomplete, radar backscatter from mixed pixels often difficult to quantify and partition into individual geophysical signal sources, spatial resolution largely insufficient, sensor frequency selections limited, and empirical-based relationships predominantly driving the retrieval algorithms. These deficiencies largely impact proper satellite-based identification of the dominant spatial and temporal scales of key variables.

Moreover, the compilation of satellite observations to build homogenous, cross-calibrated and cross-validated, long and continuous data records of climate quality, across multiple satellite missions, is also challenging. Sensors and platforms degrade with time, sometimes stop to function, and need to be replaced or substituted, often with different technical specifications and performances. Hence, even a single year with lower quality data can cause significant deviations and uncertainty for long-term climate records. The lack of in-situ Fiducial Reference Measurement (FRM) for accurate calibration and validation of satellite observations in the Arctic Ocean clearly hampers the generation and provision of homogeneous datasets. Foremost, incorporating new sensor observations to help revisiting previous processing strategies and retrieval algorithms, is still an essential step to better understand air - sea ice - ocean interactions and identify the slow-fast dynamic processes. Several initiatives have been launched by ESA to define FRM strategies for satellite observations, but these are currently limited to a few types of observations (e.g. FRM4SOC for ocean colour, FRM4STS for surface temperature, FRM4Alt and St3TART for radar altimetry-based sea surface height). These are designed to develop and apply rigorous approaches to ensure that satellite data are traceable to given S.I units with a full uncertainty budget.

In particular in the Arctic region, high-resolution satellite data may be more directly interpreted. Radar textural properties at high resolution have indeed demonstrated unique and quite straight forward abilities to detect sea ice breakup and lead formation, sea ice drift, deformation and damage, but also to detect wave pattern in ice to evaluate sea ice thinning. From an Earth-Observation perspective, an important component of the Digital Twin Ocean-Arctic (DTC) development will largely build on these high-resolution data-centric approaches to become one of the essential layer to derive these interactive digital replica of the Arctic system. This layer will inform and help to train numerical and statistical simulations about processes and feedback in response to external forces. As already mentioned, a more fractured ice cover will impact the momentum, heat, moisture, and gas exchanges between the atmospheric boundary layer and the upper ocean in the Arctic, and also strongly impact the upper ocean biology as the primary production is highly dependent on light availability.

Among high-resolution satellite data, fully-focused altimeter measurements have emerged and already demonstrated promising abilities to detect wave propagation in the highly dynamic marginal ice zone. The same has been shown using satellite sun glitter imagery such as the Sentinel-2 Multi-Spectral Instrument (MSI) for ocean wave detection in the presence of sea ice (Collard et al., 2022). All these measurements could be used to complement the Sentinel-1 measurements. While strong temperature and humidity gradients in the atmospheric boundary layer make the Arctic a very cloudy and hazy place that severely limits the availability of exploitable Sentinel-2 optical images, systematic comparisons with radar measurements will likely help to train efficient Machine Learning algorithms. While wave pattern detection from imaging spectrometers like Sentinel-2 certainly requires favourable sun illumination angle, and alignment between the instrument and the surface wave field, they provide reference measurements to help refine the retrieval algorithms from SAR nadir and off-nadir measurements.

A targeted generic demonstration is to continue to develop a more advanced physical-based model constrained with data. Already, some what-if scenarios can be simulated using existing models such as the ArcMFC within CMEMS (Bertino et al., 2021, Xie et al., 2017) and the neXtSIM (Rheinlaender et al., 2022). But continuous progresses on advances in machine learning and observations will certainly help new developments to estimate evolving sea ice mechanical properties to deliver improved kinematic forecasting capability. This new capability is a very good candidate for a DTC, as it combines advanced high-resolution EO (e.g. SAR-altimeter, SWOT, Sentinel-1 and Radarsat SAR measurements, Sentinel-2, … and associated deformation-field products), contemporary machine learning algorithms and a novel physics-based model. For instance, it can be used to better test and understand sea ice break-ups (as influenced by sea ice extent and sea ice thickness) due to strong winds and their consequences. Such developments will also further provide means to guide more direct interpretation of high-resolution EO snapshots, to envisage and manage what/if scenario questions relevant to a wide range of stakeholders need for making informed decisions. Note, operational services are crucial to the Arctic region's shipping, tourism, fishing industries and search and rescue, to meet the scientific ambitions to advance in understanding of how the sea ice reacts to climate change, and to consider climate mitigation and adaptation. In the current geopolitical climate, operations in the Arctic region may also have significant implications for national and regional security. Additionally, DTCs will be able to generate what-if scenarios using existing missions together with new approved Sentinel and Earth Explorer satellite missions to support the planning, design and operation of future satellite missions.

All in all, the approach to advance the design and implementation of a DTC of the Arctic Ocean will build on data-driven physical constrained analytics, where satellite-based multi-sensor high-resolution EO data will be combined with available in-situ data and regularly sampled numerical model fields, such as from the advanced neXtSIM sea-ice model. An Arctic Ocean DTC will help: (a) visualize, intercompare, analyze, and validate the sea ice conditions; and (b) augment the irregularly sampled satellite-based EO-data using the neXtSIM model to assess the impact of the high-resolution sea ice conditions at the larger scales and longer-terms covering the entire Arctic region.

3.1 **Summary and Recommendation**

Observations are crucial to building our understanding of the physical system. For up-to-date information on the state of the Arctic climate system, continuous monitoring and reprocessing are required to support both short-term forecasting and seasonal and decadal prediction efforts.

In the coming decade the satellite-based observation capabilities will clearly strengthen in combination with advances in machine learning and numerical modelling. Towards 2030 a new generation of high-resolution satellites including the Copernicus expansion missions (e.g., ROSE-L, CMIR, CRISTAL), the Explorer missions (e.g Harmony) and the next generation of meteorological satellites (e.g., MetOp-SG, AWS) will be launched. Complemented with the series of Sentinels (e.g., Sentinel 1, 2, 3, 6), the MAGIC mission and 3rd party missions this offers a unique and unprecedented capability to strengthen the satellite-based observation capabilities in the Polar regions. New approaches to use multiple native resolution satellite measurements (i.e. single image snapshots, altimeter transects, visible/thermal infrared, microwave imaging radiometry, scatterometry and synthetic aperture radar imagery) rather than gridded fields (that often smear important features) in a broader data-centric analysis framework will emerge. In combination with access to in-situ data, high fidelity Large Eddy Simulation (LES) experiments and advances in development of AI/ML will help better understand governing sub-grid unresolved and coupled processes (e.g. Brajard et al., 2020, Barthélémy, et al., 2022).

In that context, the Arctic Digital Twin Components continuous research will therefore secure more reliable analyses and estimates of sea ice damage, break-up, lead and polynya formation, sea ice roughness, sea ice drift, new ice formation, sea ice freeboard height, snow depth, meltwater ponds, sea ice volume and mean sea level. Better determination of fluxes driving changes in the atmospheric boundary layer, sea ice and upper Arctic Ocean is also anticipated, while better validation of higher-resolution models will strengthen assimilation, reanalyses and reconstruction of more reliable long time series.

The key remaining challenges that have emerged along the Arktalas Hoavva project are rather generic and can be summarized to the following needs:

- to provide efficient and interoperable frameworks and architectures to access data and model resources across institutions and organizations;
- to constitute large, homogeneous, curated multi-variable datasets for model training;
- to refine mathematical approaches tailored to cope with sparse data and analysis of rare and/or extreme events;
- to consider software infrastructure and common tools for supporting developments of hybrid model components.

Prioritizing the collection, synthesis and curation of reference data (including in situ, satellite, and numerical simulations) is key to create AI-ready datasets for model training and validation. Reanalysis models, assimilating satellite and in-situ observations already offer open-access data-cube facilities to help apply AI techniques (i.e. reanalysis performs a consistent dynamical space-time gridded interpolation of the different variables). Still, these models do not manage to precisely identify all the multiple and complex interactions between variables (e.g. atmospheric boundary layer, upper ocean physical and biological coupling across differing space-time scales including rare and extreme events). As such it is highly important to systematically combine the present-day available model-data cubes with direct satellite-based and in-situ based observations to strengthen the generation of AI-ready datasets.

In particular, efforts should rapidly target:

Advanced sensor synergy (extension of the RGPS approach) retrievals of sea ice drift trajectories from Sentinel-1 SAR. Building on systematic use of satellite C-band SAR data the RGPS sea ice drift and deformation product has been widely used for studying sea ice kinematics as well as for calibration/validation of sea ice models. In this respect, it was essential for stimulating the development of the next generation sea ice model (neXtSIM, Ólason et al, 2022). There is a need to re-enforce the unique capability of this method by extending observations (from visible to microwave L-band), operating at different resolution but offering a potential very high-temporal sampling. In particular, it is proposed to generate multi-satellite product to advance understandings of the sea ice dynamics and drift and to open for calibration of data-driven methodologies to downscale estimates from medium and low-resolution observations (e.g. L-band SMOS). This effort enters precursor demonstrations of model-driven strategies to demonstrate the advanced Digital Twin Component capabilities and usage to simulate complex processes that are not properly characterized in sea ice models, with targeted focus on CIMR, Rose-L, Cristal in combination with operational meteorological satellites.

Validation of the sea ice rheology on satellite data. Simulation of accurate sea-ice thickness distribution, which is especially important for predicting regional winter climate and Arctic amplification remains a challenge. Sea-ice motion plays an important role in the ice thickness distribution and a more realistic sea ice rheology is required that is consistent with the observed mechanical behavior of sea-ice. A novel metric building on multi-sensor satellite observation synergy needs to be developed to evaluate Lagrangian model simulations (e.g. neXtSIM) including detection and tracking of linear kinematic features associated with sea ice damage and lead formation. By invoking neXtSIM results as input in a Conventional Neural Network approach the output can include sea ice rheological parameters. Once trained satellite observations can then be used as input for the output retrieval of optimal parameter values.

Improving air and ocean drag coefficient parametrization in neXtSIM. Despite the strong dependence of the air and ocean drag on sea ice roughness, it is currently represented in neXtSIM by only two coefficients, which are not varying neither in space, nor in time. Recent studies show successful retrieval of ice roughness from ICESat-2 data on pan-Arctic scale but with low spatial resolution. Capitalizing on these studies it is recommended to use ICESat-2 in synergy with CryoSat-2 and Sentinel-1 to derive sea ice roughness at much higher spatial resolution. Time- and space-varying fields of sea ice roughness can then be used for computing the air and ocean drag coefficients in netXtSIM. The transfer function can be tuned using satellite-derived sea ice drift. All in all this approach will expectedly improve sea ice forecast.

Detection and characterization of marginal ice zone on Sentinel-1 SAR. ML-algorithm based on convolutional neural networks will be trained on Sentinel-1 SAR data and ice charts for robust detection of marginal ice zone dynamics and characterization of the sea ice in terms of floe size distribution. The algorithm will be applied to series of SAR images and the derived MIZ maps will be used for evaluation of the neXtSIM coupled with WW3 model followed by assimilation into neXtSIM-Wave model tested in operational setup.

Longer time series of sea ice age fraction maps. The sea ice age dataset from NSIDC is a long time series but is considered to overestimate the age in individual pixels and to deliver too high heterogeneity of the product due to the deficiencies in the advection method. A new sea ice age algorithm that provides a distribution of ice age fractions for each pixel in homogenous fields will be explored for the period 2002 to present (AMSR2 era) with an extension back to 1994 using OSI-SAF ice drift in winter and TOPAZ (or neXtSIM) reanalysis data in summer.

Simulation of CIMR brightness temperatures. High resolution CIMR radiometer data makes it more sensitive to anomalies in brightness temperature originating from narrow cracks in sea ice. neXtSIM is known to properly reproduce sea ice deformation at the model resolution and realistically simulate ice break-up. The thermodynamic part of the model can be extended to include salinity, porosity and other relevant properties of sea ice and snow. Moreover, the ice and snow emissivity model can be plugged into neXtSIm to simulate CIMR data at high resolution. The simulated data can be used for testing / developing CIMR algorithms, for instance, starting activities of assimilating CIMR data at brightness temperature level.

Ground truthing.
Capitalizing on the regular UNIS (Svalbard) field studies the opportunity to use Svalbard as a "Sustainable Climate Reference Laboratory for Earth Observation" is highly interesting for establishing time series (like the Manoa Loa CO_2 measurements). Primary products might include SST, local sea ice concentration, thickness, extent, type, snow depth, presence of meltwater ponds, salinity, water vapor and cloud liquid water. Ideally this could contribute to both pre- and post-launch Copernicus expansion missions (CRISTAL, CIMR, Rose-L and the Next generation Sentinel-3 altimeter) field campaigns. In particular, it is recommended to conduct a pilot study over a sea ice reference site in vicinity of the Svalbard including access to coincident scanning laser data take.

All in all these recommended activities will, in turn, strengthen the research and understanding of the important role of the Arctic Ocean in transition at the regional to global scales, notably regarding:

- transport of freshwater and Atlantic Water in the Arctic Ocean in the presence of declining sea ice extent;
- changes in biogeochemistry, biology and ecosystem under the transition towards a blueArctic;
- vertical mixing processes from the top of the atmospheric boundary layer to the depth of the halocline layer in the upper ocean;
- the regional water cycle, energy cycle and carbon cycle;
- teleconnection and influence on weather and climate at lower latitudes (globally in fact)

4 REFERENCES

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