ARKTALAS HOAVVA PROJECT

DELIVERABLE D-10: ARKTALAS SCIENTIFIC ANALYSES AND DATA REQUIREMENTS PLAN

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This Deliverable D-10: Technical Note (TN) is associated with Task 1: The preparation and planning of the data collection and corresponding scientific analyses. It follows the structure and outline indicated in the Statement of Work (SoW) and the Arktalas Hoavva technical project proposal. The approval of this deliverable by the Agency will set out the approach for the data collection and corresponding scientific analyses.

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Study Team

The Arktalas Hoavva (Sami for Arctic Ocean) study project (https://arktalas.nersc.no) is funded under the ESA contract number 4000127401/19/NL/LF. The team that will undertake the study is composed of four partners from Norway and France. Nansen Environmental and Remote Sensing Center (NERSC) coordinates the project with participation from Ifremer, OceanDataLab and NOVELTIS.

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1. Introduction

The aim of the Arktalas study is to: *Use satellite measurements in synergy with in-situ data and modelling tools to characterize and quantify the processes driving changes in the Artic sea ice and Arctic Ocean.* In particular, the following four major interlinked and cross-disciplinary Arctic Scientific Challenges (ASC) will be investigated:

ASC-1: Characterize Arctic Amplification and its impact

ASC-2: Characterize the impact of more persistent and larger area open water on sea ice dynamics

ASC-3: Understand, characterize and predict the impact of extreme event storms in sea-ice formation

ASC-4: Understand, characterize and predict the Arctic ocean spin-up

The Arktalas Project KO meeting took place by WebEx on 9 July 2019. The project will be executed over 24 months and be structured around the following seven tasks:

- **Task 1:** Preparation and planning of the data collection and corresponding scientific analyses;
- **Task 2a:** Arktalas Hoavva data collection and quality control;
- **Task 2b:** Implementation of analyses and visualization system;
- **Task 3:** Scientific analyses of the Arktalas Hoavva data set;
- **Task 4:** Analyses of future satellite mission impacts in understanding the change to the Arctic Ocean;
- **Task 5:** Promotion of the Arktalas Hoavva study and scientific community outreach;
- **Task 6a:** Creating a scientific roadmap;
- **Task 6b:** Final report**;**
- **Task 7:** Arktalas Hoavva Project Management

These tasks have clear links to the specific objectives expressed in the Statement of Work. They are also strongly interconnected as illustrated in the work-breakdown lay-out shown in Figure 1.

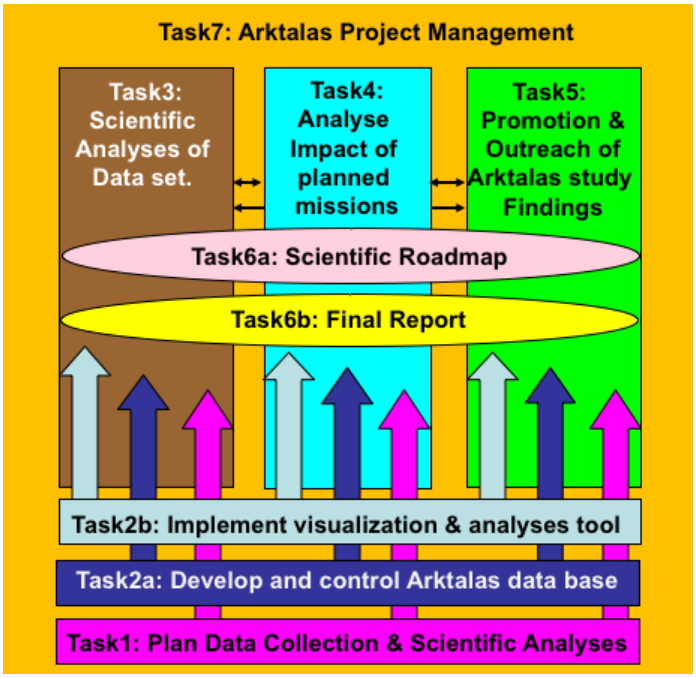

Figure 1. *Arktalas Hoavva work breakdown and approach*

Each task will have the following lead and participating partners as outlined in Table 1 below.

Task No. and Title	Start - End	NERSC	IFREMER	ODL	NOVELTIS
1. Planning and Preparation	KO – KO+3	**Lead**	Participate	Participate	
2. Data collection and quality control	KO – KO+9	**Lead**		Participate	
3. Analyses and Visualization Tool	KO – KO+12			**Lead**	
4. Scientific Analyses	KO+3 – KO+23	Participate	**Lead**		Participate
5. Impact of future missions	KO+8 – KO+21	Participate			**Lead**
6. Promotion and scientific outreach	KO – KO+24	**Lead**	Participate	Participate	Participate
7. Scientific Roadmap	KO+18 – KO+24	Partner	**Lead**		Participate
8. Final Reporting	KO+18 – KO+24	**Lead**	Participate		Participate
9. Arktalas Hoavva Project management	KO – KO+24	**Lead**			

Table 1. *Partner roles per task.*

2. Data Collection and Scientific Analyses

<u>Section 1.1: Sea ice - ocean interactive processes: Overview of present knowledge</u>

Already more than a century ago Dr. Fridtjof Nansen (1902) pointed out that *"It is evident that conditions of the North Polar Basin have much influence on climate, and it is equally evident that changes in the conditions of circulation would greatly change the climatic conditions".* Today it is understood that the changes in the Arctic climate results from a large number of cross-disciplinary interactions between the atmosphere, land, ocean and sea ice [Goosse et al., 2018]. Some of the dominant contributing processes include: the ice-albedo feedback, enhanced meridional energy transport, changes in clouds and water vapour and weak vertical mixing in the Arctic winter inversion. Understanding these processes and feedbacks and making a better representation in the climate model are crucial to reduce the uncertainty in coupled climate model simulations. However, studying feedbacks in the Arctic involves many challenges. One major challenge is that cloud feedbacks from changes in Arctic clouds are hard to isolate. The cloud radiative effect (CRE) is not only determined by the clouds themselves but is also influenced by the surface albedo and water vapor concentration. Another difficulty is that feedbacks are often studied from the top of the atmosphere (TOA) perspective. However, the Arctic sea ice and land ice respond rather to changes in the surface energy budget. Because the scattering between clouds and the surface influences the downwelling of shortwave radiation at the surface and low clouds influence the downwelling of longwave radiation, this energy budget is different from that at the TOA. Due to lack of sufficient ocean-sea ice-atmospheric interaction and atmospheric profile data it is therefore a major challenge to establish a consistent surface energy and TOA budget with reliable accuracy.

The NOAA Arctic Report Card (www.arctic.noaa.gov/Report-Card) issued by Osborne et al. (2018) in December 2018 emphasizes that continued warming of the Arctic atmosphere and ocean are driving broad change in the environmental system in predicted but, also unexpected ways. Among the signs of persistent Arctic warming highlighted in the report are:

- Surface air temperatures in the Arctic continued to warm at twice the rate relative to the rest of the globe. Artic air temperatures for the past five years (2014-2018) have exceeded all previous records since 1900.
- In 2018 Arctic sea ice remained younger, thinner and covered less area than in the past. The 12 lowest extents in the satellite record have occurred in the last 12 years.
- Pan-Arctic observations suggest a long-term decline in coastal land-fast sea ice since

measurements began in the 1970s.

- Spatial patterns of late summer sea surface temperature are linked to regional variability in sea ice retreat, regional air temperature and advection of waters from the Pacific and Atlantic oceans.
- In the Bering Sea region, ocean primary productivity levels in 2018 were sometimes 500% higher than normal levels and linked to a record low sea ice extent in the region for virtually the entire 2017/2018 sea ice season.
- Warming Arctic Ocean conditions are also coinciding with an expansion of harmful toxic algal blooms in the Arctic Ocean.
- Microplastic contamination is on the rise in the Arctic, posing a threat to seabirds and marine life that can ingest debris.

As emphasized by Smith et al., (2019) there is a growing need for operational oceanographic predictions in the Arctic polar region. This is driven by a declining sea ice cover accompanied by an increase in maritime traffic and exploitation of marine resources. The Sea Ice Outlook (SIO) by the Sea Ice Prediction Network (SIPN) is a collaborative effort to facilitate and improve sub-seasonal prediction of September sea ice extent by physics-based and data-driven statistical models. This was recently demonstrated by Chekroun and Kondrashov (2017) and Kondrashov et al., (2018a,b) (http://research.atmos.ucla.edu/tcd/dkondras/Arctic_Sea_Ice.htm) and could clearly be an important issue for the scientific analyses in the Arktalas project. However, a significant gap exists in the ocean observing system in polar regions, compared to most areas of the global ocean, hindering the reliability of ocean and sea ice forecasts. This gap can also be seen from the spread in ocean and sea ice reanalyses for polar regions which provide an estimate of their uncertainty. The reduced reliability of polar predictions may affect the quality of various applications including search and rescue, coupling with numerical weather and seasonal predictions, historical reconstructions (reanalysis), aquaculture and environmental management including environmental emergency response. Dedicated efforts are also needed to make use of additional observations made as part of the Year of Polar Prediction (YOPP; 2017-2019) to inform optimal observing system design. To provide a polar extension to the Argo network, it is recommended that a network of floating sea ice-borne ice and upper-ocean observing buoys be deployed and supported operationally in ice-covered areas together with autonomous profiling floats and gliders (potentially with ice detection capability) in seasonally sea ice covered seas. In complement to this Maksym (2019) emphasizes that a number of complex cross-disciplinary ocean - sea ice - atmosphere interactive processes and feedbacks are contributing to the sea ice decline as schematically illustrated in Figure 2. Processes depicted include: (i) ice–albedo feedback accelerating ice loss through enhanced heating of the open ocean and melt ponds driving ice melt, and heat storage in the upper ocean; (ii) enhanced near-surface heating due to radiative feedbacks; (iii) increased radiative heating from clouds and water vapor; (iv) increasing intrusion of clouds and water vapor into the Arctic; (v) increased ice motion; (vi) increased inflow of warm Pacific water; and (vii) deep convection in the Atlantic sector due to thin ice growth entraining heat from the warm Atlantic layer.

Climate models have not properly captured these changes as the coupling of natural climate variability, climate feedbacks, and sea ice is not well understood. A robust feature of climate models that is consistent with observations is enhanced warming of the Arctic relative to lower latitudes. This warming, (named the Arctic Amplification) is most often associated with the sea ice–albedo feedback in autumn (Cao et al., 2015; 2016). Snow-covered sea ice reflects most of the incident solar radiation. As the sea ice melts, it reveals the ocean, which absorbs more solar radiation. The heat absorbed by the ocean melts more sea ice, which in turn promotes more solar heating of the ocean, thus creating a positive melting feedback (Perovich et al. 2011). As the sea ice cover retreats further in summer, this sea ice loss and subsequent release of heat to the atmosphere from the ocean during autumn freeze-up, and resultant thinner ice cover through the winter and spring further warms the atmosphere near the ice surface (Screen & Simmonds 2010). More open water also implies more light penetration that may stimulate biogeochemical processes in the upper ocean (Randelhoff et al. (2019), as well as larger fetch, more wind sea development and potentially stronger winds that can further enter into the sea covered region leading to effective ice floe break-up (Kudryavtsev etal., 2019; Thomson and Rogers, 2014; Wasede et al., 2018; Mioduszewski et al., 2018). In addition, the increased meltwater run-off from land (ice sheet and snow) can trigger enhanced freshwater content in the Arctic Ocean (Kohl and Serra, 2019). Other important feedbacks that limit radiative cooling of the sea ice cover, such as increased humidity and cloud cover and a warming lower atmosphere, also contribute to Arctic amplification (e.g. Serreze & Barry 2011) and increased occurrences of polar lows (Smirnova et al., 2016). The recent book by Johannessen et al. (2020) provides a comprehensive summary of the past and present state of the sea ice in the Arctic complemented by a projected view of the future changes.

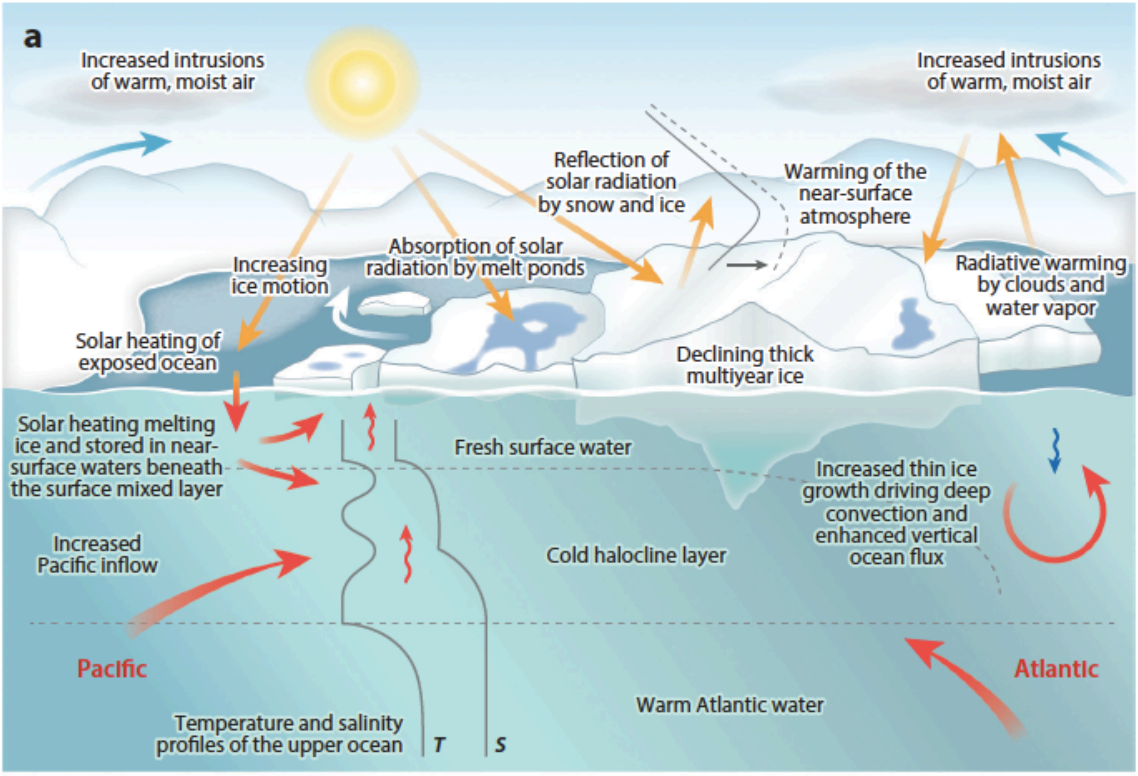

Figure 2. *Schematic of key ice–ocean–atmosphere interactions and feedbacks contributing to sea ice changes for the high latitude seas and Arctic Ocean (Maksym, 2019). Processes depicted include (i) ice–albedo feedback; (ii) enhanced near-surface heating; (iii) increased radiative heating; (iv) increasing intrusion of clouds and water vapor; (v) increased ice motion; (vi) increased inflow of warm Pacific water; and (vii) increased thin ice growth.*

Section 1.2: Key scientific questions

The multi-disciplinary, long-term, satellite-based Earth Observations (EO) form a tremendous synergy of data and information products that must be systematically and consistently explored, from the short synoptic time scales, via the seasonal and annual time scales to the longer decadal time scales. This lays the rationale for the Arktalas Hoavva study project. A stepwise multi-modal analyses framework approach benefitting from native resolution satellite observations together with complementary in-situ data, model fields, analyses and visualization system and data assimilation tools will be applied. Following this approach, the overall goal is to remove knowledge gaps and advance the insight and quantitative understanding of sea ice, ocean and atmosphere interactive processes and their mutual feedback across a broad range of temporal and spatial scales. In turn, the four interlinked Arctic Scientific research Challenges (ASC) will be investigated.

- ASC-1: Characterize the Arctic amplification and its impact?

In the high latitude seas and Arctic Ocean global warming and Arctic amplification are considered to occur across a range of quantities and their interactions and feedback mechanisms. Central among these (not exclusive) are: - changes in the radiation balance; - increased air temperature; - delayed onset of sea ice freezing; - early onset of sea ice melting; - increasing area of melt ponds and polynias; - increased lead fraction; - reduction in sea ice extent; - changes in albedo; - changes in snow cover and SWE; - changes in ocean-atmosphere momentum, heat exchange and gas exchanges; - reduction in fast ice area; - thinning of sea ice thickness; - larger fetch; - enhanced wave-sea ice interaction; - changes in optical conditions in the upper ocean with influence on the biology and marine ecosystem; - more favourable conditions for sea ice drift; - more meltwater; - more wave induced sea ice break-up; - modifications to atmospheric boundary layer and changes in weather pattern; - influence on Arctic vortex and hence teleconnection to mid-latitudes.

- ASC-2: Characterize the impact of more persistent and larger area open water on sea ice dynamics?

This research challenge is associated with: - increasing momentum transfer to the upper ocean leading to more turbulent mixing and possibly entrainment of warm Atlantic Water below the halocline; - increasing Ekman effects; - changes in sea ice growth, salt rejection and halocline formation; - larger fetch and lower frequency waves penetrating further into the ice covered regions leading to more floe-break-up; - increasing lead fraction and more sea ice melting; - reduction in sea ice flow size, age, thicknesses and extent and subsequent change in sea ice mechanical behaviour; - possibly more abundance of internal waves and mesoscale and sub-mesoscale eddies generated in the open ocean with subsequent abilities to propagate into the ice covered regions leading to changes in sea ice deformation and dynamics (e.g. Cole et al., 2018).

- ASC-3: Understand, characterize and predict the impact of extreme event storms in sea ice formation?

Growing areas of open water within the Arctic Ocean will be more effectively exposed to extreme events. A central question is eventually whether this favour increasing frequency and strength of extremes. Polar lows and cold air outbreak, for instance, are known to have strong impact in the Marginal Ice Zone (MIZ), including; - enhanced momentum transfer and vertical mixing; - enhanced sea ice formation; - enhanced formation of unstable stratification in the atmospheric boundary layer; - more low cloud formations changing the radiation balance; - set up of abnormal wave field to strengthen wave induced sea ice break-up; - abnormal impact on the pycnocline and subsequent entrainment of heat into the upper mixed.

- ASC-4: Understand, characterize and predict the Arctic Ocean spin-up?

A central question is how the ongoing Arctic amplification and subsequent changes, mutual interactions and feedback mechanisms influence the basin scale atmospheric and ocean circulation within the Arctic Ocean. This will in particular address the: - freshwater distribution and transport; - importance of Ekman pumping; - changes in water mass properties; - changes in upper ocean stratification and mixing; - changes in sub-surface heat exchange; - possibly more abundance of internal waves and mesoscale and sub-mesoscale eddies generated in the open ocean with subsequent abilities to propagate into the ice covered regions.

Section 1.3: Titles and brief outline of the six papers

In compliance with the SoW six scientific journal articles shall be delivered from Task 3. (A 7th paper to be worked-out in Task 4 shall analyse impact of future missions for the understanding of changes in the Arctic Ocean.) Each paper is expected to deliver new findings and results with relevance to at least one of the 4 major Arktalas Science Challenges (ASCs) specified in the SoW. The analyses will capitalize on the Arktalas Data Archive System (ADAS) and the Arktalas Analyses and Visualization System (AVS) and will be reproducible by the ADAS/AVS system. The tentative titles and brief abstracts are listed below. Other papers may also eventually be considered (e.g. relevance for SMOS and SMAP with other complementary observations; changing cloud conditions under Arctic Amplification, etc..).

- **Paper 1:** The paper addresses Arctic Amplification (Amplification) is commonly defined as a ratio of the Arctic warming to the hemispheric or global warming *(Relevant to ASC-1)*. The Amplification is a robust feature of climate change seen in historical observations, climate model simulations and future climate projections. The Amplification reflects stronger high-latitude climate sensitivity to changes in the net radiation balance of the climate system. To characterize the Amplification, both the forcing components and the resulting climate effects must be monitored and attributed. Although all state-of-the-art climate models reproduce the Amplification, features and parameters of this phenomenon widely vary in the simulations. The Amplification can be better characterized and constrained through satellite observations. Changes in components of the regional radiation balance could be directly retrieved from the satellite data, while the impact of the climate change on the Arctic environment could be retrieved from emerging homogenized long-term data products. The Global Inventory Modeling and Mapping Studies (GIMMS 3g) 1982-2012 exemplifies such satellite-derived climatic product that serves to monitor the changes in biological productivity through the Normalized Difference Vegetation Index (NDVI). Moreover, NASA and ESA satellites monitor essential climate variables in the Arctic region, which is generally scarce in ground-based observations. Land/sea surface temperature, sea ice extent and cloud cover, land cover types are variables with the longest history of monitoring. More recently, air chemistry, sea ice and ecosystem parameters have enhanced monitoring of the Arctic. They are useful for model calibration but do not disclose long-term trends. Climate indices may help to combine the long time periods of geographically fragmented in situ observations with dense geographical coverage of short-term remote sensing data products. Such a specific combination of the in-situ data, calibrated model simulations, and satellite monitoring opens a promising avenue to detection and attribution of the Amplification and its diverse environmental impacts. The paper will build on this rationale and recently reported findings by Chernokulsky and Esau (2019) and Chernokulsky et al (2017).

  Authors: I. Esau and A. Chernokulsky.
- **Paper 2:** Wind-waves and currents across the ice edge: Exploring mechanical effects and feedbacks with models and remote sensing (*Relevant to ASC-2).* This paper will be based on measurements of wave dissipation with little evidence of scattering. This dissipation is not yet fully understood but is presumably related to fast cycling of stresses in the sea ice and, in the presence of pancakes, dissipation in a dual phase solid-liquid system. Sentinel-1 acquisition in high resolution IW and wave modes will be used. This paper will be led by Ifremer.
- **Paper 3:** On the assessment of Arctic storm effects on sea ice dynamics, new sea ice formation and ice-ocean stress *(Relevance to ASC-3)*. In this paper, the effects of Arctic storms (Polar lows and cold air outbreaks) on the statistics of sea ice deformation and on the production of new ice will be examined. The state-of-the-art sea ice model neXtSIM (Williams et al., 2019), available at NERSC and Ifremer, will be used and intercompared/validated against a range of multi-sensor optical (cloud structure imageries), passive and active microwave data on sea ice drift, concentration and thickness, as well as novel SAR-derived drift and deformation data. This paper will be led by NERSC.
- **Paper 4:** Title: Response of Total and Eddy Kinetic Energy to the recent spin up of the Beaufort Gyre (*Relevant ASC-4)*. The Beaufort Gyre in the Arctic Ocean 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. Here a simulation performed with a high-resolution, eddy resolving model is analyzed in order to provide a detailed description of the total and eddy kinetic energy, and their response to this spin up of the gyre. On average, and in contrast to the typical open ocean conditions, the levels of mean and eddy kinetic energy are of the same order of magnitude, and the eddy kinetic energy is 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. These results have implications for understanding the mechanisms at play for equilibrating the Beaufort Gyre and the variability and future changes of the Arctic freshwater system. ***Authors:*** *H. Regan, C. Lique, C. Talandier and G. Meneghello (in revision JPO).*

- **Paper 5:** Observational evidences of eddy-sea ice interactions in the pack-ice and in the MIZ *(Relevance to ASC-2)*. In this paper the importance of interactions between mesoscale eddies and sea ice field for the on-going and future sea ice retreat (e.g Manucharyan & Thompson 2017) will be investigated. In turn, better insight of the poorly known mesoscale activity in the Arctic Ocean will be expected. Multi-sensor combinations of native resolution SAR and optical data (e.g. Sentinel-3 and Sentinel-1) combinations will be explored. This paper will be led by Ifremer.
- **Paper 6:** Impact of sea-ice friction on tidal modelling in the Arctic Ocean *(Relevance to ASC-1)*. In this study, the poorly known interaction between the tides and the sea ice cover (and grounded ice) will be investigated using a simulation model. The interaction leads to energy dissipation and is reported to have a direct effect on ice melting (e.g Padman, 2018; Lemieux et al 2018). However, the main challenge is to provide reliable parameterization of the complex sea ice cover friction at the top of the water column. This paper will be led by NOVELTIS.

Section 1.4: The Arktalas Data Set

The Arktalas Data Archive System (ADAS) will be realized as a distributed data repository and a centralized data search interface. The distributed data repository will comprise of the data archives provided by the project partners and data available from other data and service providers including ESA Scientific Hub, ESA CCI Portal, Collaborative Ground Segments, NSIDC, etc. The data will cover the pan-Arctic domain including the oceanic regions north of 55 N. Different data access and ingestion solutions will be used to facilitate easy and open access to the Arktalas data set for scientific analysis (e.g. web based, cloud solutions, on-line data processing, sftp, etc). The satellite sensor data (see Table 2) to be acquired include (not exclusive): Synthetic Aperture Radar, Passive Microwave Radiometry, Scatterometer, Visible Optical Imagery, Thermal Infrared Radiometry, LIDAR, and Altimetry. In particular, the SAR data from Sentinel-1 and, potentially, Radarsat-2 and the Radarsat Constellation, will be processed and quality controlled together with Cryosat-2 and ICEsat2 data for production of high-resolution sea ice drift, deformation and vorticity datasets. In addition, up to 5 scatterometer missions are currently in operation. Collocation of multisensory observations is therefore a highly important framework for the creation of ADAS. Note, in particular that observations from ENVISAT ASAR can be uniquely collocated with Metop ASCAT scatterometer at a 20 minutes time-lag, ensuring possibilities for highly important merging of sea ice drift and deformation estimations at different spatial scales. As the production of range Doppler fields from the Sentinel-1 A/B SAR missions are emerging, a similar promising approach will be explored combining Metop ASCAT and Sentinel-1 from 2014.

Among the future approved and planned missions focus will be towards the SWOT mission (https://swot.jpl.nasa.gov/) and the joint ESA-EU planned Copernicus High Priority Candidate

Missions (HPCM) (Copernicus High Priority Missions), notably: CIMR, ROSE-L and CRISTAL as well as the Earth Explorer 10 proposed mission HARMONY (http://www.esa.int/Applications/Observing_the_Earth/Three_Earth_Explorer_ideas_selected). In so doing, analysis from existing mission simulations will be incorporated based on availability. This is considered likely as some of the Arktalas project partners are members of the Mission Advisory Groups. This will also include investigation of detection capabilities from intermediate resolution passive microwave measurements from AMSR-2 to prepare for CIMR following the approach by Zabolotskikh and Chapron, (2019a,b) and Zabolotskikh et al., (2019). Additional data set necessary to fulfil the aim and objectives of the Arktalas Hoavva project study will include in-situ data and model output fields. However, it must be recognized that existing near-real time and off-line ocean observational efforts in polar regions are sparse and mostly connected with research field campaigns. All in all this makes collocation of in-situ data with satellite observations limited in the high latitude seas and Arctic Ocean.

Candidate satellite and sensors for sea ice and ocean observations						
Passive-µwaves	**Scatterometer**	**SAR**	**Altimeter & LIDAR**	**Spectrometer**	**Infrared**	**Gravimetry**
SMOS	Metop ASCAT	Sentinel-1 A/B	CRYOSAT-2	Sentinel-3	Sentinel-3	GOCE
			Sentinel-3	Sentinel-2	Metop AVHRR	
AMSR-2	CFOSAT	Radarsat2	Altika	Aqua MODIS	Aqua MODIS	GRACE
SSMI	Oceansat2	Radarsat constellation	ICESat ICESat 2			GRACE FO
SMAP			CFOSAT			
Aquarius						
CIMR		ROSE-L	SWOT			
		BIOMASS	CRISTAL			
		HARMONY				

Table 2: *Candidate satellites and sensors for the sea ice and ocean observations grouped into: ESA and Eumetsat missions (yellow), 3rd Party Missions (green) and new approved and planned missions (blue).*

Search interfaces will be provided to access the distributed data available via OpeNDAP, FTP or on local file servers at NERSC, IFREMER and ODL. The search interface will be realized as an online web form and as Python API e.g. in Jupyter Notebooks. The search engine will be available in Docker images or virtual machines that can be updated daily on the users' host machines. The database will be kept updated on a central server (available as docker images). As such, the user will always have an updated search interface by provisioning his/her system on a daily basis. In so doing we will detail the strength and limitations with these missions, notably:

(i) SWOT cross track width of about 120 km with an inclination of 78 degrees implies limited coverage in the Arctic Ocean, while the surrounding sea ice covered regions, notably the Marginal Ice Zones in the Fram Strait and in the East Greenland Current will be regularly monitored.

(ii) The encountered gradual widening of the Marginal Ice Zone (MIZ) within the Arctic Ocean (e.g. Aksenov et al., 2017) is expected to enrich the presence of mesoscale dynamics such as narrow ice jets and eddies, mostly manifested in satellite imagery in the Fram Strait (Johannessen et al., 1983; 1987). The range Doppler velocity from Sentinel-1 A/B can provide highly important evidences of divergence and convergence zones in the sea ice pack and MIZ. The sea-ice motion derived from SAR (Doppler and pattern recognitions) also play an important role for the sea ice thickness distribution.

(iii) Exploration to measure waves in ice, without the standard SAR processing (Ardhuin et al., 20015; Ardhuin et al., 2017) using the Doppler spectrum and the modulation due to range bunching.

(iv) Joint use of SSH and passive microwave SST data (Rio and Santoleri, 2018) also including SWOT data will improve estimates of surface currents and detection of mesoscale features in the MIZ.

(v) The promising capacity of CIMR will be essential to bring much improved spatial resolution for passive microwave measurements.

The satellite-based data will be complemented with in-situ data including fixed moorings data, ship-based data, Argo profiling floats, data from the International Arctic Buoy Program (IABP), the Ice Tethered Profilers (ITP), the Arctic Ocean Flux Buoys (AOFB) and the Ice Mass Balance Buoys (IMBB). The IABP operate a variety of autonomous Arctic buoys that measure air, sea, and ice properties. These buoys are an important component for Arctic research and application, in particular, regarding real-time weather forecasting and sea ice research in a changing Arctic environment. Currently, IABP maintains 105 reporting buoys in the Arctic Ocean. Most of the buoys are placed on sea ice, but some are placed in open water as well. These buoys have an average life-span of 18 months. The Ice-Tethered Profilers collect a full temperature profile under sea ice, from the surface down to 800 m. Analysis of these data provide a highly important view of upper ocean thermal properties in both open-ocean and ice-covered regimes. Together with these ITP profile data are the AOFBs that collect temperature profiles under the sea ice down to 5 m. Finally, the IMBBs use thermistor strings to measure ice thickness changes over the year combined with a thermistor in the ocean to get SST. In the open water from 55 N to the marginal ice zone we may access the Argo profiling floats, ship collected CTD data and data from moorings.

In addition, the ongoing MOSAIC project (https://www.mosaic-expedition.org/) lead by Alfred Wegener Institute (AWI) is presently executing a 1-year drifting field campaign in the Arctic sea ice pack that started in September 2019. It will certainly collect highly important multi-disciplinary atmosphere-sea ice-ocean data that, if and when available, might be of significant value for the Arktalas Hoavva project. Complementary fields from numerical model outputs such as forced coupled sea ice-ocean models, operational weather forecasting models, Copernicus operational services with data assimilation, ECMWF, and climate models will also be invoked. More specifically, these models include (not exclusive): neXtSIM+NEMO, YOPP fields, CMEMS, ERA Interim, WRF, TOPAZ reanalyses from 1991 to 2018 at 12 km resolution, CMIP5 simulations, NorESM and NorCPM simulations. An overview of the existing data sets that resides within the team and that will be made available in the ADAS is provided in Table 3.

Partner	**Satellite data**		**In-situ data**	**Model fields and Tools**
	Level 1	**Level 2, 3, 4**		
NERSC	Subset of SAR data from Sentinel-1 A/B Subset of SAR data from Radarsat	SIC from AMSR-2, SSMI and OSISAF; SID from OSISAF; SIT from merged SMOS and Cryosat 2; Sea ice types from OSISAF and Arctic-ROOS. Gridded Level 4 Altimetry data from ESA CCI data set	NISE, NorDataNet, Argo, ITP, IABP, NorArgo2 Research Infrastructure,	neXtSIM, HYCOM, TOPAZ, NorESM, NorCPM, LES, GeoSPaaS
ODL				SynTool visualization platform
Ifremer	Microwave radiometer from SMOS, SMAP, Aquarius, SSMI,	SIC from CCI Sea ice, CMEMS, OSI SAF; SID from CMEMS; SST from	Euro-Argo Research Infrastructure	NEMO-LIM3 coupled ocean- sea model

	AMSR; Scatterometer from Metop; Brightness temperatures from Sentinel-3; Altimetry from Sentinel-3	GHRSST, OSI SAF; sea ice types from CMEMS; SSS from pi-mep; sea ice edge contour from CMEMS; winds from scatterometer, SMOS, SSMI, AMSR		

Table 3: *Overview of dataset that are fully or partly available at repositories within the team.*

Section 1.5: The Data Access Requirements Document (DARD)

As indicated in section 1.4 a broad range of relevant data will be accessed and explored in this project (see Table 2 and Table 3). The DARD document will provide information according to a predefined structure organized by:

- Identifier of Parameter (i.e., sea ice extent, type, age, drift, current, mixed layer depth, salinity, temperature, waves, and wind);
- Platform (i.e., satellite, observation and model analysis, model forecast, and in situ);
- Sensor (relevant only wrt observations);
- Product name;
- URLs of websites (giving key information about the sensor and product),
- Version of dataset;
- Data provider;
- Spatial and Temporal coverage;
- Metadata information;
- Data volume.

Moreover, the DARD will specify: (i) Level of data and product; (ii) Projection; (iii) Spatial and Temporal resolution; (iv)Format and file organization; (v) Cal/Val and data quality references; (vi) Access restrictions and protocol; (vii) potential upgrade of products. The success of the Arktalas Hoavva project will be linked to simple and open access to data and information products. Unfortunately, this is not always the case due to restricted availability, complex access route and lack of interoperability. In complementarity with other projects and tools (such as DIAS, and ESA ITT AO9542: A new generation of linked Earth Observation data search engine) the goal is to offer appropriate abilities to discovery and access to native, coarse- and high-resolution multi-sensor satellite observations. Project partners will obtain a user account to have access to all internal datasets under the /home/project/arktalas directory.

Section 1.6: Limitations in the data availability and quality

The Arktalas Data Archive System (ADAS) may be subject to restricted availability and access to data. In general, the team cannot offer open and free access to high-resolution Level 1 SAR data, notably from Sentinel-1 A/B and/or Radarsat 2. At Level 1 we do not have authorities to distribute data, unless we have managed to obtain agreement with the data providers. This will therefore have to be dealt with on a case-by-case basis in view of the specific data needs arising within the six scientific research papers that will be delivered. In addition, it will not be possible under the given budget to establish a homogeneous multiyear database of Level 1 data at native resolution. The native high-resolution Level 1 data will therefore be fragmented and tailored to specific events and research priorities. Moreover, for Level 2 to Level 4 data ADAS will essentially contain native resolution SAR data for specific periods and regions. It will not be possible to offer full coverage of the Arctic for long duration periods.

Limitations in data availability

Sentinel-1 SAR data

- Only recent Sentinel-1 SAR L1 data is available for download from the ESA Scientific Data Hub. Historical data older than a year is stored offline and requires an extra effort and time to be downloaded. That possibly limits availability of historical data unless a dedicated access is granted to ARKTALAS by ESA or data is accumulated by a project partner.
- Historical Sentinel-1 SAR data has very poor coverage of the Beaufort gyre. Only since winter 2018 the coverage has improved.
- The Arctic ocean is routinely covered only by the Sentinel-1 SAR data in Extra Wide Swath mode with medium resolution (pixel size equals 40 m). The data in Imaging Wide mode (IW) is limited and available only approximately every 5 days in the vicinity of Greenland and Svalbard.

RADARSAT-2 SAR data

- Normally RADARSAT-2 data is not freely available for users outside Canadian government services. However, there is a possibility to initiate a research project with Environment Canada through our colleagues Dr. Stephen Howell or Dr. Alex Komarov. Access to a limited archive of RADARSAT-2 datasets can potentially be granted covering the Beaufort gyre region for period of interest.

Passive microwave data and products

- Due to surface melting of snow and sea ice in summer many algorithms fail to provide reliable results (e.g. ice drift). The processing is therefore stopped by the data producers and the products are not available in summer. This concerns mostly coarse resolution products such as sea ice drift, sea ice type, sea ice thickness from AMSR-2 and SMOS.

Altimetry data and products

- Due to the relatively low repeat cycle of the CrySat-2 (30 days sub-cycle) the full coverage of the Arctic ocean at reasonable resolution can be achieved only after one - two weeks of observations. That limits the frequency of availability of sea ice thickness observations.

Limitations in data quality

Sentinel-1 SAR data

- Due insufficient correction the Sentinel-1 SAR products suffer from the thermal noise contamination that cannot be fully corrected using the annotation data from the auxiliary information accompanying the datasets. A method for thermal noise removal developed at NERSC has to be extended for processing data after the new IPF software update at the ground receiving station.

Passive microwave and SAR -based products in summer

- Due to melt ponds on sea ice occurring in summer many products based on passive microwave or SAR data are limited in quality. Such products as, e.g. PMW ice concentration, SAR ice drift, SAR ice edge, etc. are still produced during summer but their reliability is lower. This is partly reflected in the value of uncertainties accompanying the product, but the uncertainty values can be underestimated compared to the actual errors in the products.

Section 1.7: The Arktalas Analyses and Visualization System

The implementation of the Arktalas Hoavva Analysis and Visualisation System (AVS) allows users to browse the data hosted in the Arktalas Data Archive System (ADAS) and display them on a map at full resolution. AVS will provide an intuitive web interface to browse and display the EO data sets collected for the Arktalas case studies, offering a graphical support for project members and external users to discuss their results, explore the synergy between available products and potentially discover new interesting cases.

The AVS will be based on the Syntool software suite developed by OceanDataLab: it has been used in the past to create other EO data visualization websites like the Ocean Virtual Laboratory (https://ovl.oceandatalab.com) and the GlobCurrent (https://globcurrent.oceandatalab.com) portals for example. Syntool is composed of a web interface where the data are displayed on an interactive map and a set of Python processing tools that transform EO data into PNG images or GeoJSON files that the web interface is able to load and render in most recent web browsers. Some configuration is needed to adapt the web interface to the project requirements (title, logo, products list, etc...) but no new development is foreseen for this component since it has already been used to create web portals in polarstereo projection for the Arctic region, such as the SWARP portal (https://swarp.oceandatalab.com) .

The Python processing tools are already able to read some of the data sets identified for the Arktalas case studies, but most of them are not supported yet and will require the development of tailored data readers to extend the tools capabilities. The implementation of these data readers requires some choices to be made regarding the optimal values range and scale used for storing data, or the colormap that will convert values into colours when the data will be transformed into images for example. A Syntool test portal containing the output of data readers under ongoing development will be available for experts who work on case studies that involve the new data sets. With access to this portal, they can provide feedback and validate the data readers before they are used to process larger amounts of data, making sure that the implementation choices are relevant for the needs of the project.

The AVS is meant to facilitate scientific analysis and exploitation of the data made available within the ADAS, it is therefore necessary to create a software component that will allow the AVS processing tools to exploit the ADAS search capabilities and access its data (see Figure 3). The development of this component will start once the ADAS specifications have been defined. For instance, if the ADAS specifications provide data access using a public URL, then it would be possible to include download links directly in the AVS web interface, allowing users to quickly download the data they see on the map.

AVS includes independent tasks that can be realized in parallel: for example a developer can add support for new products by implementing specific data readers while another one implements the system for requesting data (a “client” in the “client-server” model) from the ADAS. A new feature allowing the Syntool web interface to load data from multiple backends has recently been developed and is currently in test phase. If this evolution is validated, it would be possible to avoid the centralization of all the data in a single massive storage system by distributing the Arktalas data among several infrastructures and make the whole system more resilient (fallback) and scalable (distribution).

One infrastructure (at least) must have both an ADAS and an AVS backend (i.e. Syntool processing tools and the ADAS client) before large amounts of data can be processed. The availability of this infrastructure is a choke point which could delay the realization of the AVS but it should not be a concern until a later stage of the project as most tasks are upstream of this prerequisite. Once an infrastructure hosting both an ADAS and the AVS backend is available, data processing can start and the web portal can be deployed to display results as soon as they are produced by the Syntool processing tools. The Arktalas AVS could therefore be online very quickly and be exploited in the early stages of the project, even if it will only be containing a limited number of data sets at first and then offer additional data sets when new data readers are ready.

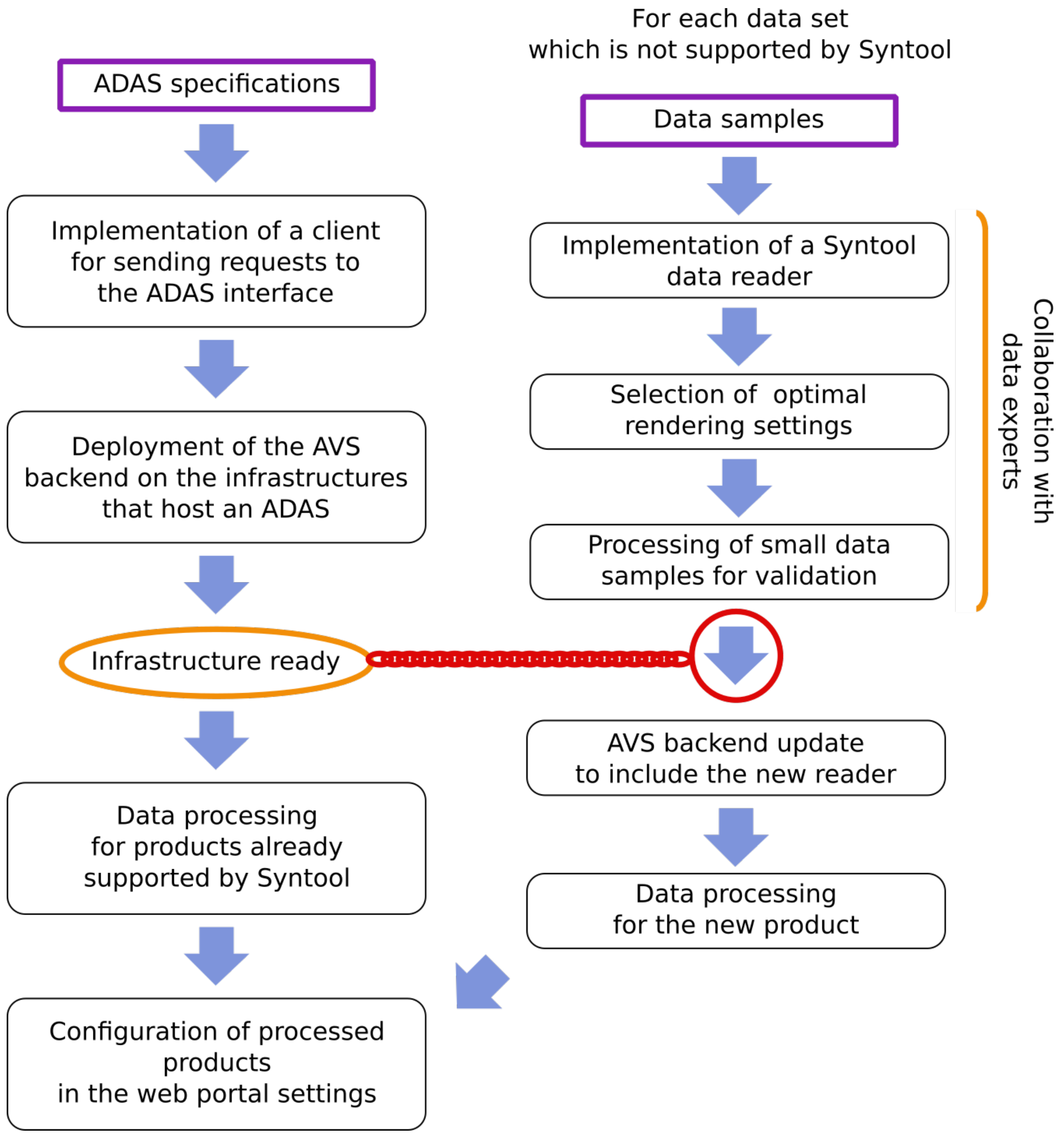

Figure 3. *Schematic illustration of the functions of the Arktalas Analyses and Visualisation System (AVS) including the connection to ADAS.*

Through the course of its existence, the Syntool software suite has been installed on many different Linux systems, virtual machines and containers (Docker, LXC, nspawn). It has also been deployed on NERSC, IFREMER and ODL facilities for other projects, so there should be no technical issue when deploying the AVS on the infrastructure of these partners. Provided the ADAS and AVS backend are hosted on multiple platforms, the backend-related test procedures will have to be customized for each infrastructure unless they share a common virtualization technology. U user manual will be written once all major developments are complete, i.e. when the ADAS client and all the data readers have been implemented.

Section 1.8: Connection and interaction with other relevant ongoing projects.

Good contacts and dialogues with relevant EC, ESA and national funded projects and activities will be established in order to maximizing collaborative research and cross-fertilization among activities. Candidate projects and activities (not exclusive) include:

- EU funded: YOPP, INTAROS, Eu PolarNET, KEPLER, BLUE-ACTION, APPLICATE, ARICE, ICE-ARC, ICUPE, NUNATARYK, NextGEOSS (https://nextgeoss.eu), CMEMS, CMEMS WIZARD; DIAS.
- ESA funded: CVL, MOIRA, Arctic Mission System Study (AMSS), SMOS+Sea Ice, Arctic+Salinity, ESA CCI (sea ice, clouds, sea level budget closure, ice sheet and glaciers), SKIM Report for Mission Selection, Copernicus High Priority Candidate Mission (HPCM) studies (to be launched soon), notably the following 3 missions: CIMR, CRISTAL and ROSE-L.
- National funded: FRASIL (NO, FR), Nansen Legacy (NO), SHOM study (NO, FR), Ifremer funded PostDoc (FR), UBO, Brest funded PhD (FR, UK), IMMEDIAT (FR).
- Other relevant international funded field campaigns, projects, reports and meetings: MOSAIC, ICARP (Arctic Science Summit Week 2015 in Toyama, Japan (23–30 April, www.assw2015.org), STPI-SAON, US lead IABP, Arctic Report Card, 2018. EU-PolarNET White Papers and the development of the Integrated European Polar Research Programme.

In this way the Arktalas+Hoavva study will contribute as part of a cluster of projects and activities that will bring insights from a broad range of complementary Earth system sciences and expertise together, thus allowing one entry point to Arctic research. This will, moreover, strengthen the ability to take out mutual synergies and prove a reliable approach to advance Earth system monitoring and research in the fragile environment of the high latitudes and Arctic region, such as connected with the energy cycle, water cycle and CO2 cycle. In turn, it will also foster stronger international engagement and cooperation in promoting sustainable development and in interacting with policy makers, indigenous peoples and local communities, as well as business and NGO representatives and other societal actors.

A rolling archive of relevant links to projects, websites and servers will also be maintained during the project. Presently the list include:

- http://cci.esa.int/
- http://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Arctic
- Swarp - *SWARP develop downstream services for sea ice and waves forecast in the Marginal Ice Zone (MIZ) in the Arctic.*
- Arctic ROOS - *Arctic ROOS promote, develop and maintain operational monitoring and forecasting of ocean circulation, water masses, ocean surface conditions, sea ice and biological/chemical constituents.*
- Seascope arctic – under construction
- Cryosat mission - *ESA's CryoSat mission is dedicated to measuring the thickness of polar sea ice and monitoring changes in the ice sheets that blanket Greenland and Antarctica.*
- Polarview - *Polar View is the world's leading organization for the provision of operational, satellite-based monitoring of the polar regions and the cryosphere.*
- KEPLER - *Key Environmental monitoring for Polar Latitudes and European Readiness*
- INTAROS - *Integrated Arctic Observation System*
- Copernicus - *Marine environment monitoring service*
- http://marine.copernicus.eu/about-us/about-producers/arctic-mfc/
- https://www.nersc.no/project/arc-mfc
- http://cmems.met.no/ARC-MFC/index.html

- The Nansen Legacy - *Pioneering research beyond the present ice edge*
- CVL (ESA funded)
- MOSAIC program - *Embark on the largest polar expedition in history.*
- S1-Denoise (ESA funded)
- MOIRA (ESA funded)
- ESA´s planned Copernicus High Priority Missions
- https://arcticdc.org/
- https://www.arcticobserving.org/
- https://datacite.org/
- https://ccadi.ca/
- Towards Machine Learning https://www.earth.com/news/machine-learning-arctic-sea-ice/
- New techniques http://research.atmos.ucla.edu/tcd/dkondras/Arctic_Sea_Ice.htm
- https://en.wikipedia.org/wiki/Arctic_sea_ice_decline
- Arctic Regional Ocean Observing System http://nsidc.org National Snow and Ice Data Center (NSIDC)
- http://osisaf.met.no, Ocean and Sea Ice Satellite Application Facility (OSISAF – Eumetsat and MET.no)
- https://sites.uci.edu/zlabe/arctic-sea-ice-figures/

An expert group of international recognized scientists have moreover been established and include: Dr. Ron Kwok, NASA/JPL, Pasadena, US; Prof. Vladimir Kudryavtsev, RSHU, St. Petersburg, Russia; Dr. Stephen Howell, Environment of Climate Change Canada, CLI-REC, Ontario, Canada; and Dr. Alexander Chernokulsky, A.M. Obukhov Institute for Atmospheric Physics, Moskva, Russia. They will all be invited to attend the open science meeting.

3. Summary

The content of the TN-1 deliverable will be presented and discussed at PM-1: Progress Meeting 1 at the Nansen Center in Bergen, Norway (January 2020, exact date to be agreed). In closing of PM-1, the baseline activities for the Arktalas Hoavva project study shall be approved by the Agency. In so doing, the TN-1 document will be refined and the priority data collection, scientific analyses and dedicated research activities associated with the 6 scientific papers (tailored to the 4 major Arctic Scientific Challenges) will be implemented for execution in the Arktalas Hoavva project.

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