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Acronyms

AD	Applicable document
ADB	Actions database
ADS	Analysis Dataset
AMOC	Atlantic Meridional Overturning Circulation
ATBD	Algorithm theoretical basis documents
BEC	Barcelona Expert Center
CCD	Closure Contract Documentation
CCI	ESA Climate Change Initiative
CDOM	Colored Dissolved Organic Matter
CDR	Climate Data Record
CMEMS	Copernicus Marine Environment Monitoring Service
CliC	Climate and Cryosphere
CSIC	Consejo Superior de Investigaciones Científicas
DIR	Directory
DNB	Debiased Non-Bayesian
DUM	Dataset user manual
EC	European Commission
EO	Earth Observation
EOEP	Earth Observation Envelope Program
ESA	European Space Agency
ESL	Expert Support Laboratory
FR	Final review
FWF	Freshwater fluxes
GCOS	Global Climate Observing System
IAR	Impact assessment report
ICM	Institute of Marine Sciences
ITT	Invitation to tender
KO	Kick-off
L2OS	Level 2 Ocean Salinity
LSC	Land-Sea Contamination
MR	Monthly report
MTR	Mid-term review
MTS	MIRAS Testing Software
MV-TN	Modelling and validation technical note
NS	Nodal sampling
PM	Progress meeting
PMP	Project Management Plan
PSU	Practical Salinity Unit
PVR	Product Validation Report
RB	Requirements baseline
RD	Reference document
SMAP	Soil Moisture Active and Passive
SMOS	Soil Moisture and Ocean Salinity
SoW	Statement of work
SR	Scientific roadmap
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TDP	Technical data package
UPC	Universitat Politècnica de Catalunya
VIR	Validation and intercomparison report
VR	Validation report
WCRP	World Climate Research Programme
WP	Work package

1 Introduction

1.1 Scope of this document

This document holds the Final Report (FR) prepared by Artic+ Salinity team, as part of the activities included in the [WP000] of the Proposal (Task 0 from SoW ref. EOP-SDR/SOW/084-17/DFP). This document fulfils the validation element to deliver this project.

The objective of this document is to summarize main findings and results of the Arctic+ Salinity project (or simply Arctic+ from here on). This document make reference to different deliverables produced along the course of the project. Hence, in order to avoid duplicity of content with other documents, the reader is encouraged to consult relevant deliverables (Table 1).

1.2 Structure of the document

The FR is structured as follows:

Section 1 describes the objectives of this document.

Section 2 Provides an overview of the project including task, overview and outreach activities.

Section 3 Describe the technical development of the project including a description of the achievements, challenging areas of the project and the lessons learned within the course of the project

Section 4 Presents a short summary of the project findings.

Section 5 Settle the final conclusion of the project and description potential post-project steps.

1.3 Applicable documents

Table 1 Applicable documents

ATBD	Algorithm Theoretical Baseline Document	Arctic+SSS-D3.1-ATBD_v1.0
DUM	Data User Manual	Arctic+SSS_DUM_D1.1_v1r2
URD	User Requirement Document	SSS_cci-D1.1-URD-i1r0
PSD	Product Specification Document	SSS_cci-D1.2-PSD-v1r4
RBD	Research Baseline Document	Arctic+SSS_RBD_D1.2_v1r6
SoW	Statement of Work	ref. EOP-SDR/SOW/084-17/DFP
PVR	Product Validation Report	Arctic+Salinity_WP400_PVR_v2r1
IAR	Impact Assessment Report	Arctic+Salinity_WP500_IAR_v1.0

2 Project overview and context

2.1 Project Overview

Sea Surface Salinity (SSS) retrievals from satellite L-band sensors are well understood. However, SSS retrievals at high latitudes proved to be a challenge. The purpose of the Arctic+ Salinity (here after, simply Arctic+) project was to develop a satellite retrieved SSS product to further the understanding of the observed changes in freshwater fluxes within the Arctic region. The Arctic+ project delivered all the expected deliverables as presented in the Technical Proposal (Table 2). The project made two cycles of data production, which resulted more time consuming than initially planned. However, at end of the Arctic+ project there was a significant improvement (ref. PVR) of SSS data (version v3.1), which was also used to developed internal science cases to improve model assimilation system TOPAZ (ref. IAR).

A summary of the project status is presented in the table below (Table 2):

Table 2. Project status for all tasks and work packages. All the referencing project documentation is available at https://arcticsalinity.argans.co.uk/documentation/

Task	Work package	Deliverable	Status
0. Management	WP000	FR Website	Completed
1. Scientific Requirement Consolidation	WP100	RBD	Completed
2. Data Collection	WP200	DUM	Completed
3. Algorithm Development & Validation	WP300	ATBD	Completed
	WP400	PVR	Completed
4. Scientific Analysis and Impact Assessment	WP500	IAR	Completed
5. Science Roadmap	WP600	SciRM	Completed

The objectives of project and its assessment at the end of the project were as follow:

Table 3 Project Objectives

No	Challenge	Assessment
1	Develop a new algorithm and novel approaches with the aim of producing the best quality SSS product of the Arctic region of well-characterized accuracy.	Achieved
2	Generate a long term salinity dataset from 2011 up to date to be publicly offered to the scientific community, and in particular will be shared with ArcFlux team to explore synergies.	Achieved
3	The observed dynamics and its link with Arctic processes, as for example freshwater flows, E-P, ocean circulation will be studied.	Achieved
4	Assess the relation between the dynamics of SMOS salinity with land freshwater fluxes (Greenland and glacier flows) and ocean freshwater fluxes (rivers and E-P) using model outputs. This has the objective to quantify the freshwater fluxes with SSS products.	Achieved

5	Assess the impact of the new data in a data assimilation system (the TOPAZ4 system, both in forecast and reanalysis mode) with the idea that if an improvement is demonstrated the assimilation of SMOS products on TOPAZ will become the new Arctic reanalysis and forecast products on the CMEMS portal.	Achieved
6	Roadmap description of future work to better characterize the Freshwater fluxes for the Arctic regions.	Achieved

All the objectives of the Arctic+ project were successfully met along the course of the project in different task (see section 2.2, task 1-6). The science contribution of the Arctic+ project encompasses from building a rich data set collection of best in situ observations to be used as most reliable *true value* to be compared to the satellite retrieved measurements.

2.2 Project Tasks

According to the Project overview, several tasks were fixed under three different Work Packages (WP). Before starting the project, they were set as follows:

Table 4 Project work packages description

Work package	Description
WP000	Support project delivery, meet milestone requirements
WP100	Review of the state of the art, identify dataset, models and test areas to be used for the successive development and validation tasks. Produce the associated risk analysis. Report the constraints for methods and models to be produced in the activity
WP200	Collect the necessary and relevant datasets for the development of the activity. Provision of access to the collected dataset to the scientific community via web
WP300	Select methods and algorithms on the basis of a detailed experimental analysis of the potential alternative methods and approaches supported by a sound inter-comparison and validation. Describe the final version of the algorithms. Execute a scientific analysis of the results justifying the development choices and the associated trade-offs.
WP400	Provide a sound inter-comparison and validation.
WP500	Analysis of the experimental dataset to investigate its dynamics and its links with Arctic processes. Use river flow data and other datasets and models to explore new approaches to connect salinity dynamics to land-ocean fresh water fluxes at regional scale targeting quantification of freshwater fluxes. Produce and publish the Experimental dataset and integrate it with the Analysis dataset. Compare the results with existing results quantifying the improvements. Analyse the errors/uncertainties of the final products. Investigate the potential of the products to enhance the current knowledge and state-of-the-art. Determine the benefit and impact of the results on the specific test areas considered in RB Estimate the benefit and impact of the results on the scientific and operational areas.
WP600	Analysis of the experimental dataset to investigate its dynamics and its links with Arctic processes. Use river flow data and other datasets and models to explore new approaches to connect salinity dynamics to land-ocean fresh water fluxes at regional scale targeting quantification of freshwater fluxes.

	Produce and publish the Experimental dataset and integrate it with the Analysis dataset. Compare the results with existing results quantifying the improvements. Analyse the errors/uncertainties of the final products. Investigate the potential of the products to enhance the current knowledge and state-of-the-art. Determine the benefit and impact of the results on the specific test areas considered in RB Estimate the benefit and impact of the results on the scientific and operational areas.

2.3 Project Outcomes

The main outcome of the project was intended to provide a SSS retrieved product especially dedicated to enhance the science capabilities in the Arctic region.

The SSS retrieval algorithm included:

1. Implementation of Arctic regional grid to minimize the spatial interpolation errors and to respect SSS gradients.
2. Application of debias method at brightness temperatures (T_b), Level 2.
3. Computation of SMOS-based TB climatology
4. Inversion to salinity data and production of the products

To measure the improvement made each change step within the Algorithm chain, the SSS BEC v2.0 served as baseline product reference (ref. PVR). The Arctic+ SSSS product showed clear improvements in key study areas distributed in different locations in the Arctic region (Figure 1),

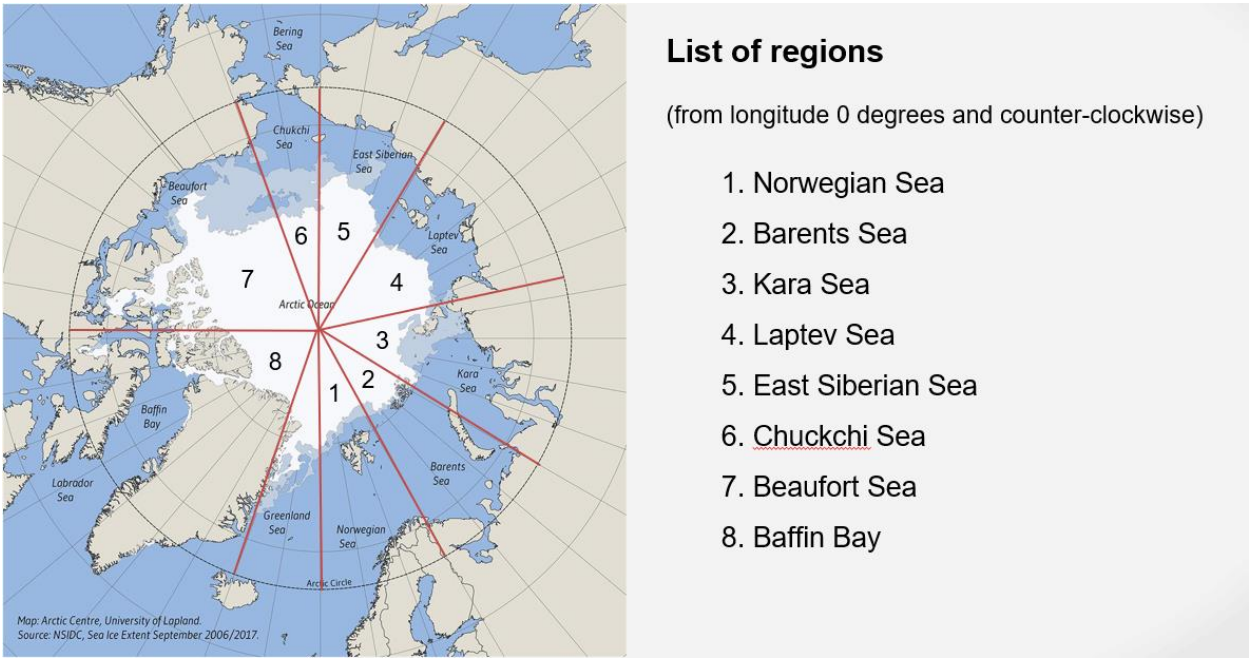

Figure 1: Geographical splitting of the Arctic region to produce metrics separately for each segment of the TARA expedition (ref PVR).

The main improvements Arctic+ SSS product were:

1. Increased number of valid retrievals within the Arctic region
2. Usability of the polar grid (EASE v2.0)
3. Better effective spatial resolution
4. Satellite (SMOS) data only, to minimize error uncertainty due to external data sources uncertainties.

There were other improvements, which were commonly related to comparison SSS against in situ observations, i.e. Argo and TARA data.

The Arctic+ SSS was the only satellite data that did not include external sources of information. On the contrary, SSS BEC v2.0 used an Argo based climatology to reduce the seasonal variability seen in SMOS data. Hence, SSS BEC v2.0 comparisons against Argo were not scientifically valuable to measure the quality of the product.

Arctic+ SSS comparisons against TARA data (i.e. ship based observations in the Arctic), showed improved statistics in some key science regions like the Beaufort Sea with respect v2.0.

As seen in different aspects of the project in situ observations were scarce, limited in space and in time. This data scarcity was an expected restraint that affected mainly the validation of SSS. Hence, to mitigate the lack of in situ observations, the PVR presented the **Correlated Triple Collocation (CTC)** method (see PVR, section 5.2) and the **Wavenumber Spectrum Analysis** (See PVR, Section 5.3).

The CTC, served to compute the *Error of Variances* of triplets of SSS satellite retrieved data (i.e. SSS BEC v2.0, Arctic+ v3.1 and SMAP). The methodology is thoroughly described in González-Gambau, et al., 2020. The results of the CTC might suggest that from all the satellite SSS data included in the PVR, Arctic+ v3.1 resulted to provide the most reliable geophysical information with smaller errors. The results of the wavenumber spectrum analyses, confirmed that Arctic+ SSS v3.1 has better effective spatial resolution than the other products analysed, which contribute to better description of the oceanography processes taking place in the Arctic ocean.

The science outcomes of the project included the **assimilation of Arctic+ SSS v3.1 into TOPAZ system** (ref. IAR), resulted generally beneficial for most test sides. Furthermore, the use of the new product forstudies of the Freshwater content , showed a benefit in some regions, e.g. Beaufort Sea. However, comparisons against ground truth were limited due to lack of observational data. Hence the interpretation of those results needs further analyses. Finally, study of using CDOM and SSS data showed improvements of the dynamic characterization and variability of the river outflow into the Arctic.

2.4 Outreach

This has been a challenging component of the project since the arrival of the global pandemic COVID-19 (March 2020). The way of working has been via tele-networking; however there were

significant science contributions in a form of virtual conference (Table 5) and there are plans to submit three peer review works to present the Arctic+ SSS v3.1 to the community (ref. ScRM). The topic to each paper will be as follow:

- Paper with the **presentation of the product and its validation (started)**. This will be sent to the Earth Science System Data Journal (https://essd.copernicus.org/), which is a journal especially dedicated to the publication of articles on original research datasets, furthering the reuse of high-quality data of benefit to Earth system sciences. (BEC)
- Paper with applications when using the Arctic+ SSS product. This will contain the analysis of correlation between SSS and Chl in the Arctic river discharge area. This initial study is reported in the IAR, but further work is required for publication. (BEC)
- Paper with the results of the assimilation of the Arctic+SSS product on TOPAZ. (NERSC)

Table 5 List of workshops where the work has been presented (ref. ScRM)

Workshop	Place and date	Title of the presentation	Type
Atlantic from Space	Southampton, UK January 2019	Arctic and North Atlantic Sea Surface Salinity retrieval	Oral LINK
ESA Living Planet	Milan, May 2019	Arctic+ Salinity: Retrieving Sea Surface Salinity in a Challenging Environment	Poster
Ocean Predict symposium 2	Halifax (Canada), May 2019	Evaluation of Arctic Ocean surface salinities from SMOS and two reanalyses against in situ data	Oral
IGARSS	Yokohama (Japan), July 2019	Arctic Sea Surface Salinity retrieval from SMOS measures	Poster LINK
Salinity Science Seminar	Hamburg, September 2019	Satellite SSS and simulated SSS in the Arctic (NERSC)	Oral
CCI Salinity Science Seminar	Hamburg September 2019	Overview of the Arctic+ Salinity ITT (BEC)	Oral LINK
AGU	San Francisco, EEUU December 2019	Arctic salinity from space: Monitoring the freshwater system.	poster
Ocean Science Meeting	San Diego, EEUU February 2020	Continental and sea ice melting signature in Arctic sea surface salinity.	Oral
CLIVAR/CliC Northern Ocean Regional Panel, NORP	February 2020	A new SSS product based on SMOS.	Webinar
ISAR - CANCELLED	Japan, March 2020	Assessment of the correlation between river discharge and sea ice growing in Laptev Sea	poster
EGU	online April 2020	BEC: CMEMS session: The SSS assimilation results	Oral Link

International Symposium of Marine Science	Online July 2020	ICM: Assessment of the correlation between river discharge and sea ice growing in Laptev Sea.	Oral
EO4 Polar Science	October 2020	ICM: Assessment of the correlation between SMOS and Sea Surface Salinity, river discharge and Sea Ice Fraction in Latpev and Kara Seas	Poster
EO4Polar Science (BEC)	October 2020	Remote Sensing to better assess the Arctic Freshwater fluxes budget - knowledge gaps towards improvements in collaboration ARCFLUX team (Henriette Skourup)	Discussion session
EGU Session OS4.6 – The Copernicus Marine Service (CMEMS)	2021	Impacts of assimilating Arctic surface sea salinities from SMOS in a coupled ocean and sea ice reanalysis	Pico Oral

The knowledge gained within Arctic+SSS project contributed to develop other proposals to further understanding the SSS retrievals in the polar regions (i.e. including Arctic and Southern Ocean), or to advance on the understanding the upper ocean dynamics in at high latitudes. Some of this contributions were listed in the Science Roadmap (ref. ScRM) as follow:

- **CRIceS, H2020-LC-CLA-2020-2** (**approved** will start in September 2021): The upper ocean halocline is a regulator of and impacted by processes at the ocean/sea-ice interface. So, the ARCTIC SSS products developed in this project will be used to be compared with the salinity output of the current models participating in CMIP6. (**ICM**)
- **ARCTIC-MON, proposal submitted to the Agencia Estatal de Investigación (AEI) - Spanish funding (waiting for resolution)**: We propose to produce Arctic ocean classification product departing from the Arctic+SSS product to better asses and compute the freshwater budget and fluxes. (**ICM (PI)**)
- **Advanced insights into the Beaufort Gyre freshwater system from Space (ABS). ESA AO/1-10461/20/I-NB, ESA POLAR SCIENCE CLUSTER ITT (not priorize at the moment):** This project has the focus on understanding of the Beaufort Gyre freshwater system. This project builds on the knowledge and data obtained from 13 individual projects: 11 ESA projects (ArcFlux, Arctic+salinity, CryoTEMPO among others) and 2 EU/EC projects. It will use range of Earth Observation (EO) data from satellites (Arctic+salinity product), in-situ and ocean & atmospheric reanalysis data during the Cryosat-2 era (2011-present). (**NERSC (PI) and ICM**)
- **Southern Ocean Freshwater (SO Fresh), ESA AO/1-10461/20/I-NB, ESA POLAR SCIENCE CLUSTER ITT (APPROVED , KO 17 May 2021):** Has the objective to derive sea surface salinity product from the Souther Ocean in collaboration with Southampton University. It will benefit of knowledge gained thanks to Arctic+ salinity, and also some software will be re-used. (**ARGANS (PI) and ICM)**

- **Pacific modulation of the Sea level variability of the Beaufort Gyre System in the Arctic Ocean**, ESA Dragon cooperation (**approved**). The sea level variability of the Beaufort Gyre (BG) is influenced by the changes in steric height and ocean mass. Hence the freshwater and heat stored in the BG can have significant impact on the sea surface height. Arctic+ SSS data will be used to link between SSS and freshwater content of the region estimated from available in-situ observations. (**NERSC (PI)**).

3 Technical viability analyses

3.1 Project Successes

Project successes included the delivery of all expected deliverables (Table 2) and met at certain degree all the objectives (Table 3) set at the beginning of the project. As described earlier (see section 2.3), the major outcome of the project included:

1. Production of a dedicated SSS product, which has been proven to add an important science value to the community in the Arctic ocean.
2. There was a successful model assimilation of Artic+ SSS product into TOPAZ system. The results of the TOPAZ model output showed there were regions (e.g. monitoring of some river outflows, Fresh Water Content within Beaufort Sea, etc.) with an improvement after assimilation of Artic+ SSS data.
3. The Arctic+ project was positively received within the Arctic science community. Different project working in the Arctic will use data produced in the Arctic+ and others will benefit from the knowledge gained within the Arctic project.
4. Effective engagement with key data distributors (i.e. including COPERNICUS/CMEMS, EMONET and PANGEA) will ensure there is wide spread data distribution within the science community.

3.2 Project Challenges

The challenges identified were the following:

- A better SSS Arctic climatology with more in situ data could improve the product. This was a limitation for all the teams working with salinity data in the Arctic. For that, a large team of scientists prepared a white paper with a project proposal to NASA, entitled “A NASA high latitude salinity Campaign” asking for financial support to developed a campaign to measure the SSS in the Arctic and Antarctic in different regions and periods. For more information read the Roadmap document.
- The land-sea contamination induces errors (mainly biases) on the retrieved SSS near the edge of the land. The land-sea contamination is mitigated in the current algorithm by subtracting the corresponding SMOS-based climatological value of brightness temperature to the measured value of brightness temperature, then adding back a good estimate of such climatological brightness temperature. The ice-sea contamination is not well corrected by the latest version of the retrieval algorithm. Since the edge of sea ice is not constant, and therefore a single SMOS-based climatology cannot correct the contamination effects. Even though this effect was taken into account by discarding any sea ice concentration greater than zero, new algorithms are required. We propose to modify the correlation efficiency by means of a small percentage of change of the non-zero baseline elements of the Gkj matrix, as described in Corbella et al. (2015). For more information read the Roadmap document.

3.3 Project Performance and Lessons Learned

The lessons learned during the Arctic+ SSS project are enumerate bellow:

- Performing the debiasing non-Bayesian method at TB level have not shown improvements with respect the debiasing at SSS level (as done at the v2 product). In fact, based on work done in other semi-enclosed sea, we have noticed that the application of the debiasing at SSS level has resulted to be more effective (in terms of biases removing) than the debiasing in TB. Therefore, for future developments of the Arctic Ocean product, we propose to work with debiasing non-Bayesian at SSS level.
- It is preferable to avoid using any external source of data to perform the temporal correction of the data, so not using ARGO data neither any numerical model to have a SMOS dataset independent to any external source. Therefore, to perform the temporal correction we propose to compute global maps. Then, to compute the global mean from those maps and to impose that in time, the global mean is equal to the global mean of a constant salinity reference.
- The new grid projection performed at L1 shown good performance in version v3.1, since it reduces the number of interpolations, thus produce an improvement of the resolution of small spatial scales. We propose to maintain this type of projection. For more info, read the ATBD report.
- From the Baltic+ Salinity ESA ITT, we have learnt that the behaviour of biases and errors on SSS is very different at the different values of SST. Therefore, it is necessary to include SST as an additional parameter for defining SMOS-based climatology. That is, besides of separating the values in categories depending on longitude, latitude, xi, eta and overpass direction, they must also be separated depending on SST, because different SSTs lead to different biases and different errors due to the drastic changes with SST in the sensitivity of brightness temperatures to SSS.

4 Summary of Project Findings

The impact that represents the Arctic+ SSS project was remarkable in different aspects that will make a noticeable contribution to the Arctic Science community. These contributions included technical aspect that will be useful to the SSS satellite community in general, like:

- Development of SSS retrieval algorithm performing the debiasing technic at brightness Temperature level (ref. ATBD). However, the SMOS based Tb climatology was not ideal for the retrieval. This was an important lesson learned for the Algorithm development that might be avoided in future studies.
- Definition of the optimal methodology for SMOS SSS validation in the Arctic (ref. PVR), which also include the use of other analyses than statistical comparisons of the differences between $SSS_{satellite}$ versus $SSS_{insitu\ at\ 10m}$. These advanced validation techniques were the Correlated Triple Colocation method and the Spectral Analyses, which proved to be useful validation techniques.
- Arctic+ SSS assimilations in the TOPAZ showed to improve the model assimilation, especially in river outflow locations. The assimilation schema developed in Arctic+ project will be used in next assimilation Copernicus assimilation programme for the Arctic system.

Arctic+ salinity product presented in this document may aid the Arctic Scientific community in promoting the current state of the art of different oceanographic challenges. The science applications of SSS in the Arctic will go beyond the science applications seen along the course of this project (see IAR). Therefore, SSS data produced within this project will be included in the Essential Climate Variables (ECV) inventory (v3.0) (ref. To ECMF ECV inventory website)

Several scientific studies based on the new product have been started and other ideas are proposed in this document which need further development.

Moreover, the new daily TB product used to derive the SSS product could be released to scientific community.

The team has gained knowledge on how to process SMOS TB measurements in cold waters regions. This knowledge will be useful for future developments to produce SSS in the Southern Ocean, for example.

5 Conclusions

This report marks the endpoint in a project to determine the technical and scientific potential of the developed algorithms. The findings of this work are promising on SSS retrievals in the Arctic Ocean, and in the Polar regions in general.

During the duration of the Arctic+ project, work concentrated in the development, validation and production of a SSS dedicated product for the Arctic ocean. The production of the Arctic+ SSS data proved to be more challenging than the initially expect. Hence, the activity took longer than expected (~20 months instead of 15 months). However, despite the delayed in the satellite data production, the Impact Assessment of the product proved the science viability of the Arctic+ product to enhance science work taking place in the Arctic Ocean.

There is the need to further explore the science results obtained from the assimilation system and from the different science cases. The Arctic+ project would benefit from an extended working plan to further develop science analyses and to further ensure the engagement with the science community, e.g. presenting the Arctic+ data to the Polar Clusters community (expected in September 2021). A continuation beyond Arctic+ projected time, would allow the Arctic+ team to finalise dedicated Science Cases (ref. IAR and ScRM). Some of the science work continuation would be:

- Improvements of the TOPAZ reanalysis system aimed at better reproducing the interannual variability of freshwater fluxes: interannual river fluxes from the Arctic HYPE model, inclusion of Greenland Ice Sheet mass loss.
- To improve knowledge about the boundaries of freshwater budget in the Arctic, using Arctic+ SSS in combination with improved altimeter data, gravimetry data, sea ice thickness and drift data, river discharges and ocean water transports.
- Dedicated studies of the freshwater pulses originating from glacial melt episodes over Greenland and other Arctic glaciers on Novaya Zemlya, Svalbard.
- Preparatory work towards the CIMR high-priority Copernicus mission.
- The salinity trend analysis to further understand decadal analyses of the freshening observed in the Beaufort Sea contrasted with Barents Sea and Laptev Sea.
- Further understanding of the correlations seen between SSS and CDOM maps, especially in those regions near to edge of the ice melt and within river outflows

The continuation work to further exploit the science application of the Arctic+ data would allow promote collaboration with other teams who have in situ campaign measurements to verify the results.

An error analysis assessment has been performed inter-comparing JPL SMAP v4.2 SSS, BEC SMOS Arctic SSS v2.0, and BEC SMOS Arctic v3.1 products. The Correlated Triple Collocation method has been used and it shows that BEC v3.1 has smaller error than BEC v2.0 except in the Hudson Bay, Eastern coast of Greenland and Kara sea. JPL SMAP product is the one with larger errors of

the analysed. Moreover, the spectral analysis showed that the BEC SMOS Arctic v3.1 product is the one with better effective spatial resolution.

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