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ASSESSMENTS OF THE IMPACT OF SNOW DEPTH AND FREEBOARD PRODUCTS ON THE PERFORMANCE ON SEA ICE FORECASTS.

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1. INTRODUCTION

The EU-funded Coordination and Support Action 'Key Environmental monitoring for Polar Latitudes and European Readiness - KEPLER' (see https://kepler-polar.eu) started in January 2019 and ended in June 2021. Among its main tasks were the identification of research gaps (*Gabarró et al.*, 2021) and the development of a roadmap towards an improved European capacity for monitoring and forecasting the Polar Regions (*Kauker et al.*, 2021). Such a capacity clearly relies on the combination of numerical models with data streams provided by space-borne sensors and in-situ measurements. Within KEPLER a number of observational scenarios were evaluated in terms of their performance in a data assimilation system. In the construction of these observational scenarios we put emphasis on the Sentinel satellites of the Copernicus programme (see https://www.copernicus.eu) with particular focus on the Copernicus expansion missions, i.e. the missions for expansion of the Sentinel fleet. The project evaluated two types of observational scenarios, one addressing sea ice forecasts and the other one addressing land-based fossil fuel CO_2 emissions. Here we focus on the former type of scenarios.

2. METHODS AND DATA

Our main tool for the evaluation of observational scenarios is the Arctic Mission Benefit Analysis (ArcMBA) system (*Kaminski et al.*, 2018), which evaluates in a mathematically rigorous fashion the observational constraints imposed by individual and groups of EO data products by using the quantitative network design (QND) approach (*Kaminski and Rayner*, 2017). The system was developed within the ESA-funded A+5 study (see https://arctic-plus.inversion-lab.com). The ArcMBA tool quantifies observation impact (added value) of a (potentially large and heterogeneous) set of observations through the reduction of uncertainties in a set of relevant target quantities simulated by a coupled model of the sea ice-ocean system. The model we employ is the Max-Planck-Institute Ocean Model (MPIOM) (*Jungclaus et al.*, 2012), i.e. the sea ice-ocean component of the Max-Planck-Institute Earth System Model (MPI-ESM) (*Giorgetta et al.*, 2013), in a computationally efficient global setup with zoom over the Arctic.

The basic idea behind the QND approach is to back propagate the uncertainty from a set of observations (in reverse sense through the modelling chain) to a control vector that contains the uncertain variables which enter (and control) the simulation. In a second step the uncertainty in the control vector is mapped forward to an uncertainty in selected target quantities. In our case the control vector encompasses a combination of initial and boundary conditions as well as parameters in the process formulations and in the observation operators (*Kaminski and Mathieu*, 2017) required to simulate equivalents of the observations.

The target quantities for the present study are 1-week to 4-week forecasts of sea ice volume (SIV) and snow volume (SNV) for selected regions along the Northern Sea Route and the Northwest Passage as well as for the entire Arctic. Our assessments assume observations are assimilated in April 2015,

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with the respective 1-week and 4-week forecasting periods starting on May 1. We assume consistently for all observational scenarios that the model provides correct sensitivities. This has two consequences: First, the differences between the observation impacts of the respective scenarios are most pronounced. Second, we provide an optimistic (but consistent) view of the impacts of the respective observational scenarios. Another point worth noting is that our reference for the observation impact is a simulation without assimilation of any observations. This clearly yields higher observation impact than adding a new data stream to a (possibly operational) reference setup that already assimilates many other data streams. Finally the observational uncertainties that we assume for the planned future missions are based on currently available information and plausible, but they can always be refined when further information becomes available.

3. RESULTS AND DISCUSSION

A comprehensive set of experimental results derived with the ArcMBA tool is provided by *Kaminski et al.* (2018) and in *Kaminski et al.* (2021). We hence restrict the presentation of results to a few examples.

Our first two observational scenarios address altimeter measurements from the CryoSat-2 (CS2) and the Sentinel 3 (S3) missions. We focus on radar freeboard (RFB) products, because the A+5 study had identified RFB as the data product with the highest impact when compared to sea ice thickness or sea ice freeboard products (*Kaminski et al.*, 2018). The CS2 RFB product is based on actual retrieval and is provided with per-pixel uncertainty ranges (*Hendricks et al.*, 2016). In contrast, the S3 product is hypothetical and assumes the same spatial coverage as the CS2 RFB product, but with a pole hole north of 81.5N and a 4 times higher sampling frequency. In our evaluation S3 RFB outperforms CS2 RFB in the selected target regions relevant for marine transportation in the Arctic because of the higher temporal coverage. The larger pole hole of S3 is irrelevant. While this is trivial for the selected target regions relevant for shipping (too far away from the pole hole), S3 outperforms CS2 as well for the Arctic-wide assessment, i.e., the total ice and snow volume in the Arctic (two key variables for monitoring of the state of the Arctic climate system) are better constrained by S3 than by CS2. This means the higher sampling frequency of S3 overcompensates for its pole hole.

The next set of scenarios also builds upon a finding of the A+5 study, which had indicated good complementarity of RFB with snow depth (SND) products (*Kaminski et al.*, 2018). We hence constructed three hypothetical SND products and evaluated them in combination with the CS-2 RFB product. The first SND product is intended to look like a SND product to be expected from the Copernicus expansion mission CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter). The second SND product is intended to look like a SND product to be expected from the Copernicus expansion mission CIMR (Copernicus Imaging Microwave Radiometer). The third SND product is intended to look like a SND product to be expected from modelling approaches that combine a dedicated snow model forced by a numerical whether prediction model (reanalysis) with a satellite derived ice drift product to calculate the temporal and spatial evolution of SND (reanalysis-based product). When combined with CS2 RFB, the CIMR-like and CRISTAL-like SND products yield a strong gain in forecast performance. The same holds for the reanalysis-based product. Although the differences for these assessments are small, CIMR shows the best performance among the three products.

The CRISTAL SND product would be derived from the difference of two freeboard measurements on board the same platform. An alternative is the direct assimilation of two freeboard products into the model. For this purpose we constructed a LFB product that mimics an ICESat-2 product. The combination of CS2 RFB and this ICESat2-like LFB shows the overall best performance for both, SIV and SNV. This is because the assumed accuracy of the LFB (2 cm) was higher than the accuracy of the SND products. Furthermore, a general finding in previous work may come into play here: Assimilation of the raw freeboard products is more beneficial than the assimilation of derived products.

Another set of observational scenarios addressed the combination of the CS-2 RFB product with in situ observations from a hypothetical Arctic-wide network of up to 123 buoys. These scenarios yield much weaker performance than any of the above scenarios which combine CS-2 RFB with a satellite product. Leaving out the boys in the Russian economic zone clearly degrades the performance along the Russian coast.

A further observable we evaluate is SST. Our standard scenario is based on the product retrieved by OSI-SAF from infrared (IR) measurements, and is contrasted with a scenario that uses a SST product to be expected from CIMR. The performance of the CIMR-like SST product is better than that of the standard IR-based SST product. Although the IR product is more accurate, the better spatial coverage (owing to its capability to penetrate clouds) renders CIMR attractive for predicting SIV and SNV along the shipping routes.

4. CONCLUSIONS AND OUTLOOK

The ArcMBA system is an ideal framework to assist the formulation of mission requirements (for example for new Earth Explorer or Sentinel missions) or the development of EO products. Through an end-to-end simulation it can translate product specifications in terms of spatio-temporal resolution and coverage, accuracy, and precision into a range of performance metrics. Alternatively, it can translate requirements on forecast performance into requirements on the respective observables, i.e. it can help in the formulation of mission requirements. As demonstrated in the present study, the joint assessment of products from (constellations of) multiple satellites is one of the particular strengths of the ArcMBA approach. This type of assessment can be performed for higher level products (sea ice thickness/sea ice concentration) but also for products with a lower processing level (freeboard/brightness temperature).

The model response at observational times and locations as well as the target quantities can be precomputed and recorded, so that the actual assessment of a particular data set requires only matrix multiplications and inversions and can be performed in a highly efficient manner. This would allow that the ArcMBA system could be used as an interactive tool to assist decision makers, for example, in a meeting. An obvious extension would be the implementation of a user interface, or even an online tool just for this purpose.

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