The Arctic Marine Forecasting Center in the first Copernicus period

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Abstract: The period 2015-2021 has diversified the portfolio of modeling products dedicated to the Arctic. The addition of waves, tides and ocean carbon variables satisfy more adequately the users in the industry, academia and public sectors. Many validation metrics have also been introduced, providing more intuitive measures of the quality of the forecast. The resolution of several products has increased, particularly the horizontal resolution of the sea ice forecasts thanks to a stand-alone sea ice model based on a novel rheology. At the end of the Copernicus 1 period, physical and biogeochemical products come from different configurations of the TOPAZ model system, plus a stand-alone sea ice forecast from the neXtSIM model and forecast and hindcast from an Arctic configuration of the WAM wave model.

Keywords: Arctic, ocean forecasting, sea ice model, wave model, biogeochemical model, data assimilation

1. INTRODUCTION

At the start of the Copernicus Services, the Arctic Monitoring and Forecasting Center (ARC MFC) was offering four products with forecasts and reanalyses of the physical and biogeochemical variables. These were all based on the TOPAZ system, which used the Ensemble Kalman Filter data assimilation to assimilate satellite ocean observations (Sea surface heights and temperature), sea ice observations (concentration and drift) and in situ T/S profiles (from Argo and Ice-Tethered Profilers) in a coupled physical-biogeochemical model. The use of such an advanced assimilation system in operational settings was unique and still is today. The HYbrid vertical coordinate Ocean Model HYCOM was the ocean model, coupled to the CICE sea ice model using an Elasto-Viscous-Plastic rheology and coupled online to the Norwegian Ecosystem Model (NORWECOM) for the biogeochemical model as well. All products had a resolution of 12.5 km or coarser - interpolated to a polar stereographic projection - and 28 hybrid z-isopycnic layers, interpolated to the 12 “Levitus" vertical levels. None of the Arctic MFC models was nested into the Global MFC system.

2. MAIN DEVELOPMENTS

2.1. Waves

A pan-Arctic operational wave forecast product (see the overall domain on Figure 1) has been first setup using the WAM model code from the MyWave FP7 project. The code has been modified by MET Norway to allow wave propagation under the sea-ice (Sutherland et al. 2019). The sea ice concentration, ice thickness and surface currents are all taken from the ARC MFC physical forecast. In 2019, the model horizontal resolution was increased from 8km to 3km and two forecasts were run each day, alternatively for 5 days and 10 days horizon.

A wave hindcast was later added to the CMEMS catalogue at 3km resolution with an updated version of the WAM code. It included new physics, a reformulation of the mean wavenumber and mean frequency as well as a new formulation for detecting freak waves. The code has been modified as well by correcting the growth of the waves in very high winds and by allowing propagation of waves under the sea ice as in the forecast. A sub-grid scale parametrization of "obstructions" is used. At the surface the model is forced by hourly winds merged between winds from the ERA5 reanalysis and a downscaled 2.5 km non-hydrostatic convection-permitting atmospheric model Harmony-Arome hindcast for the region around Norway, shown as the rectangle in Figure 1.

The wave products are used for navigation purposes, support to offshore operations and downscaling to coastal wave models, among other uses. The 3 km products have high enough resolution to fill the mandate of Norwegian preparedness services (search and rescue, oil spill response) and have replaced pre-existing national systems.

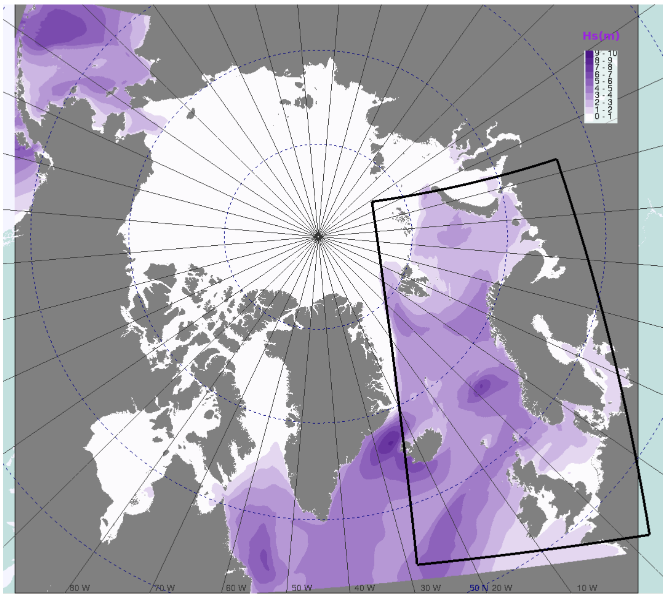

Fig. 1 Domain of the Arctic wave model. The shading colors are significant wave height (Hs) in meters. The small domain indicates the region of downscaled winds in the hindcast product.

2.2. Ocean physics

The high-frequency signals (tides and storm surges) were introduced in March 2020, with a pan-Arctic 3km configuration of the 3-dimensional HYCOM-CICE model that includes tides and other high-frequency storm surges. At the lateral boundaries - which are close to the ones of the wave model shown in Figure 1 - the Global High Resolution MFC forecasts are used in addition to tidal heights and currents computed from the FES2014 tidal database with 34 tidal constituents.

The model is intended to become the main workhorse for ocean physical and biogeochemical forecasts. It has therefore been set up with 50 hybrid z-isopycnic layers. Hence, in addition to the surface tide forecasts, the model is capable of internal tides prediction.

As for the wave products, the model resolution of 3km is also adequate for the Norwegian national mandate and has replaced a pre-existing national forecast system providing boundary conditions to coastal models around mainland Norway and Svalbard.

2.3. Sea ice rheology

The production of the TOPAZ4 reanalysis has previously shown a lack of sensitivity of the rheological model. A new sea ice model based on a brittle type of rheology - the Brittle-Bingham-Maxwell rheology - has thus been developed in a Lagrangian coordinate (the neXtSIM model, Rampal et al. 2016) to improve the simulation of sea ice drift and other related sea ice properties. This model has been set up in stand-alone forecast mode for the Central Arctic including a nudging term to daily satellite sea ice concentrations. The neXtSIM-F forecasts show much more detailed sea ice features than TOPAZ4 (Figure 2, where in particular the leads and land-fast ice are not visible in TOPAZ4) and their motions are as well more accurately forecasted, with drift distance errors cut from 8 to 4 km per day. The sea ice forecasts are used in navigation services.

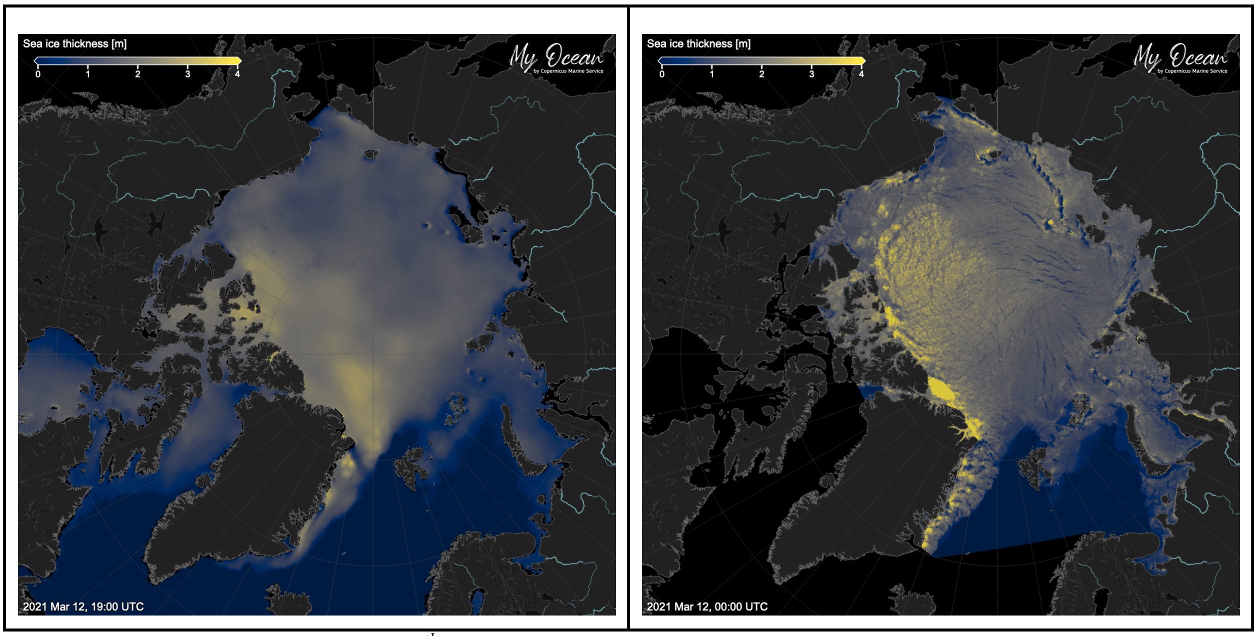

Fig. 2: Sea ice thickness on the 12th March 2021 from the TOPAZ4 system and the recently introduced neXtSIM-F forecast (right).

2.4. Biogeochemical modeling

The biogeochemical model coupled to the ocean model has been updated twice in the course of the Copernicus 1.0 period. The first upgrade in April 2016 has replaced NORWECOM with ECOSMO (Dæwel and Schrum 2013), which parameters were re-tuned to avoid an excessive amplitude of the Spring bloom.

In a second upgrade planned for May 2021, several changes are brought to ECOSMO: a doubling of both horizontal and vertical resolution (6 km and 50 hybrid layers) and the simple assimilation of satellite surface Chlorophyll data (Uitz et al. 2006), the inclusion of the carbon cycle, of light transmission through sea ice and improvements of the model inputs (rivers discharge from the Arctic-HYPE model, atmospheric deposition of nutrients from the EMEP model and lateral boundary conditions from the Global MFC model PISCES). The Framework for Aquatic Biogeochemical Models (FABM) software now couples ECOSMO to HYCOM. When compared to independent Chlorophyll profiles from the BGC-Argo buoys in the Nordic Seas, the assimilation alone reduces drastically the errors (Figure 3). The improved accuracy of the primary production is an important prerequisite for the simulation of the carbon cycle and thereby provide up to date information about the ocean carbon pump and ocean acidification.

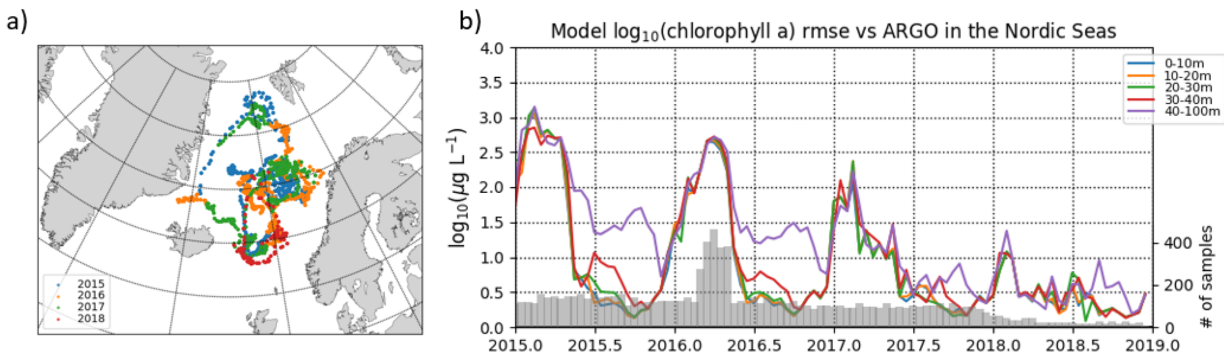

Fig. 3: comparison of simulated Chlorophyll profiles to BGC-Argo buoys (panel a). The model root mean square error (RMSE) is shown in panel-b, note the inclusion of surface chlorophyll from satellite in January 2017 and the logarithmic scale for concentrations.

Beside the developments of the forecasting product, the biogeochemical reanalysis has adopted an Ensemble Kalman Smoother (EnKS) to assimilate both satellite surface Chlorophyll data and nutrient profiles. The EnKS optimizes biogeochemical model parameters in ECOSMO using data from posterior week and can correct the timing of the Spring bloom in a biogeochemical model. The resulting reanalysis product is the first demonstration of an EnKS in CMEMS.

2.5. Physical data assimilation

The ARC MFC has started assimilating sea ice thickness products with the thin ice product from the SMOS satellite in both the reanalysis and forecast products using the EnKF in 2017. The merged product from the two satellites CryoSAT-2 and SMOS was then assimilated, first in reanalysis, then in near-real time in November 2020. The resulting improvement of the sea ice thickness persists a few months through the summer when the satellite products are unavailable.

The physical reanalysis product is being updated: the vertical resolution of the HYCOM ocean model has been doubled and the CNES/CLS Mean SSH Rio2018 reference has replaced a model time-mean to assimilate the sea level anomalies. Other new features of this reanalysis include the freshwater discharge related to the Greenland mass loss and an improved assimilation of salinity profiles. The newly introduced ESA CCI products are now systematically assimilated throughout the whole reanalysis period, removing discontinuities in the previous physical reanalysis (Xie et al. 2017). The new reanalysis product should therefore be better suited for climate studies.

2.6. Enhanced validation

Objective forecast evaluation metrics are provided monthly to CMEMS for dissemination. In addition, the products are monitored on a weekly basis by our team. Due to its relevance for operations in the Arctic, the position of the ice edge is particularly scrutinized using two metrics, the integrated ice edge error (IIEE) and the fractions skill score (FSS). Melsom et al. (2019) have reviewed these metrics.

The validation of wave parameters uses satellite altimeter data (Bohlinger et al. 2019) for both the forecast and multiyear products. This has increased dramatically the spatial representativity of the validation activity in view of the very small number of wave buoys available in the Arctic.

2.7. Ocean Monitoring Indicators

The Nordic Seas is an area for key climatic processes in the North Atlantic. The ARC MFC has therefore established two sets of Ocean Monitoring Indicators that monitor North Atlantic - Arctic Ocean exchanges through the Nordic Seas. First the exchange of water across the straits that separate the two basins and where the exchanges of North Atlantic and Arctic waters with their characteristic temperature and salinity are monitored by moorings. Then, the sea ice export from the central Arctic to the south was later also included since it represents an important part of the sea ice budget in the Arctic.

The ocean monitoring indicators thus make highly valuable data accessible to many users interested in the Arctic, without requiring them to download discouraging amounts of data.

3. CONCLUSION AND PERSPECTIVES

The Arctic MFC now offers twice as many products as initially and now include waves, tides and the ocean carbon variables. The new products have up to 4 times higher resolution than six year ago, both horizontally and vertically and adhere to the CMEMS standard naming conventions. The products offered at the end of Copernicus 1.0 have improved performance, more targeted quality checks and easy access to important monitoring indicators, which make them better suited to user needs.

After having introduced a few independent products, it will be necessary to improve their mutual consistency. The first step should be to provide the physical forecast at higher horizontal and vertical resolution. A second step will be to synchronize the slow variability of the tidal model to the data assimilative ocean forecast model. The consistency between the waves and the ocean model can also be improved using wave input terms into the ocean model (Ali et al. 2019).

The ocean forecasts also need improved bathymetry data around Greenland and near-real-time forecasts of river discharge as from the Arctic-HYPE hydrological model. The ocean reanalysis should increase its spatial and temporal resolution, to be more suitable for downscaling near the coast, and as well enhance its accuracy by assimilating sea level anomalies from the SWOT mission, sea surface salinities from the SMOS mission as prepared in the ESA Arctic+ Salinity project. The stand-alone sea ice model should also include the assimilation of sea ice deformations from Sentinel-1 SAR ice drift as well as the breaking of sea ice by waves in the marginal ice zone (Boutin et al. 2021). When available, the ocean and sea ice data from the High-Priority Copernicus Missions CIMR and CRISTAL should be assimilated too.

We also plan to distribute the ensemble forecasts from the TOPAZ system, and improve their uncertainty estimates by matching them to ensemble predictions from the ECMWF. The quality monitoring of sea ice forecasts can also be further enhanced (Palerme et al., 2019).

Ocean biogeochemistry products would benefit from a longer (3 decades) multiyear time series. The ECOSMO model would be improved by using a more advanced sinking scheme developed in the SE project ZOOMBI and should include a sea ice biogeochemistry model.

Besides the HYCOM applications, a non-assimilative NEMO configuration for the Arctic which exhibits encouraging oceanographic properties for the study of the Atlantification of the Arctic (Lind et al. 2018), this NEMO prototype should also include wave terms and online coupling to a biogeochemical model.

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