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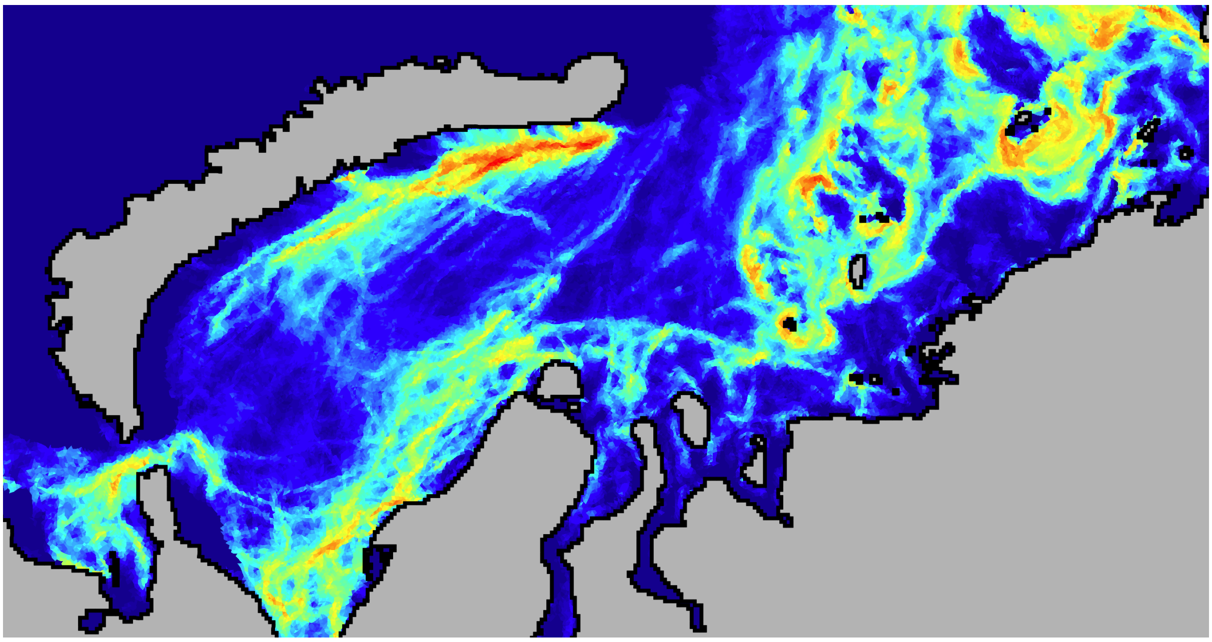
Towards a next generation sea ice forecasting platform covering the Barents and Kara Seas

TOTAL

NERSC Technical Report no. 377

Final Report of the one-year project extension



by
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Bergen, 18 October 2017

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REPORT

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Final report for the project extension: "Towards a next generation sea-ice forecasting platform covering the Barents and Kara Seas"

Executive Summary:

This project is a one-year extension of the project: "Towards a next generation sea-ice forecasting platform covering the Barents and Kara Seas" that was funded by TOTAL and conducted from summer 2014 till summer 2016 at the Nansen Centre in Bergen.

The goal of the project extension was to increase and further evaluate the forecast quality of the current neXtSIM-F forecasting platform and to improve the dissemination of the results to end-users.

The first part of the report mainly covers the activities that took place between June 1st 2016 to May 31st 2017 and that were financially supported by TOTAL. This part also includes some developments done in parallel to the Kara project, but that are still of interest for TOTAL, for example the extension of the EB rheological framework to Maxwell EB. The second part of the report presents a successful example of the use of the outputs of the neXtSIM model for planning and routing in near real-time a vessel navigating in ice-infested waters. This work was done after 1st July 2017 and was not planned in the agreement with TOTAL

As of today, the developed platform is able to provide on a daily basis accurate information on the sea ice concentration, thickness, volume of ridged ice and drift at a resolution of about 3 kilometers for the Kara and Barents Seas region, although it can easily be applied on other regions, or extended over the whole Arctic for a coarser resolution of 5 kilometers. The assimilated data either come from satellite data or from ice charts that are used operationally by ship captains. From the successful real-time use of the neXtSIM-F platform conducted this summer with SHOM, the collected feedbacks showed that the outputs are useful for planning operations and for guiding ships in ice-invested areas. In the future, it may be more relevant to use such forecasts than using ice charts or SAR images, because they are available, offer prediction, are easy to read for non-specialists and are easy to download even with low internet bandwidth.

Preliminary remarks and deviation from the plan

In this project, three tasks were conditioned to the selection of the SOFIA project. SOFIA is a proposal that was submitted to the call H2020-EO-2016 under the EO-3-2016 topic "Evolution of Copernicus services", LEIT (Leadership in enabling and industrial technologies) and got a very good evaluation from EU (13/15) but was unfortunately not selected. As a consequence, two tasks out of these three tasks have not been implemented. These are:

- to develop the assimilation of sea ice deformation and
- to test the dissemination of neXtSIM output via the e-navigation software developed by NAVTOR (http://www.navtor.com/navstation.html).

However the third task has been implemented, but is not used in the neXtSIM-F platform in its current default configuration and will then not be presented in this report:

- The implementation of a thin ice category in neXtSIM

Planned tasks

Below is a list of the tasks as listed in the project description.

1. *Forecast improvements*

   a. Data assimilation for initialization improvements

   We propose to further develop our assimilation schemes to include the following data:

   - OSISAF ice concentration (which requires to be done consistently with the current SMOS ice thickness assimilation)
   - ~~Ice damage derived from measured sea-ice deformation (**in-kind** and conditioned to the selection of the SOFIA project for the H2020 program)~~
   - CryoSat ice thickness

   b. Technical improvements to the forecasting platform neXtSIM-F

   - Increase code efficiency by switching from Matlab to C **(partial in-kind)**
   - Increase the coastlines accuracy of the Barents/Kara model domain

   c. Physics improvements to the forecasting platform neXtSIM-F

   - ~~Multi-category ice model to better represent convergence zones (**in-kind** and conditioned to the selection of the SOFIA project for the H2020 program)~~
   - Tune drag parameters to match forecasted and measured ice drift

2. *Forecast evaluation*

a. Automated evaluation against near real-time satellite-derived products with good spatial coverage

- Forecasted sea ice drift will be validated against low-resolution OSISAF drift provided by MET Norway (http://osisaf.met.no/p/ice/lr_ice_drift.html).
- Forecasted sea ice concentration will be validated against OSISAF ice concentration provided by MET Norway (http://osisaf.met.no/p/ice/)
- Forecasted sea ice thickness will be validated against SMOS ice thickness provided by the University of Hamburg (http://icdc.zmaw.de/1/daten/cryosphere/l3c-smos-sit.html)

b. Evaluation dedicated to specific processes

- Simulated sea ice drift and deformation will be compared to high resolution sea ice drift and deformation data derived from the analysis of SAR images.
- Simulated sea ice thickness fields will be compared to Cryosat along-track thickness measurements.

3. *Forecast dissemination*

- Each forecast will consist of the following variables (new proposed variables are in italic):
    - concentration
    - thickness
    - drift (u,v)
    - *rubble ice and ridged ice volumes*
    - *daily maximum (cell averaged) ice pressure*
    - *daily averaged convergence/divergence*
- Uncertainty estimates obtained from the comparison of the forecast against observations will be provided for the concentration, thickness and drift variables.
- For the duration of the extension forecasts will be provided daily as netCDF files from the NERSC thredds server (http://thredds.nersc.no/htredds/catalog.html) and graphically, along with automatic forecast evaluation, on a dedicated website hosted by NERSC.

4. *Deliverables*

- Intermediate reports at month 4 and 8.
- Final report at month 12.
- 1 publication to be submitted in a peer-reviewed scientific journal

PART 1: Work done during the one-year extension.

1. Forecast improvements

1.1 Data assimilation of satellite-derived data

As for weather forecast and operational oceanography, short term sea ice forecasts critically depend on initial conditions. With the even larger number of satellites flying nowadays, especially the ones from the EU-Sentinel series of missions, a large amount of information is available in near real-time and can therefore be potentially used for initialization. Those data however are not free of random errors, gaps and biases, and it is the role of the data assimilation scheme to include those data in the forecast system with care.

1.1.1 Assimilated data

The Kara setup that ran operationally from November 2016 to June 2017 is based on the assimilation of two independent sets of satellites-derived real-time data:

- the SMOS thin ice thickness data and
- the AMSR-2 sea ice concentration data.

Those data have different characteristics and limitations, that have to be taken into account when assimilating them into a sea ice forecast system.

The SMOS ice thickness is derived from the SMOS passive microwave radiometer and is provided daily on a polar-stereographic 12.5 km grid by the Integrated Climate Data Center in Hamburg. The satellite footprint is about 35-50 km. The retrieval error is commonly higher than the measured thickness for ice thicker than 50 cm due to the saturation of the signal, and is also very dependent on ice salinity, snow thickness, ice temperature, and ice concentration. No retrieval is available during the melt season because the retrieval method relies on the ice being colder than the underlying ocean. The SMOS data are only valid where concentration is close to 100%.

The AMSR2-ASI ice concentration is provided daily by the University of Hamburg. The ice concentrations are calculated from daily averaged brightness temperatures measured by the Advanced Microwave Scanning Radiometer 2 (AMSR2) and that are interpolated onto a 3.125 km polar stereographic grid. The satellite footprint is about 5 km. The AMSR2 concentration data is sensitive to weather noise, land spill effect and has larger uncertainties for thin ice. Those effects are taken into account by the data assimilation scheme as follows:

1) the weather noise causes rapid variations of about 0.1 for high concentration to 0.2 for low concentration. We only apply assimilation when the difference between the simulated and observed

concentrations is larger than this noise level. As the concentration is bounded between 0 and 1, using a simpler nudging method would introduce biases for high and low concentration.

2) the land spill effect introduces fake ice concentration near the coast in the AMSR2 datasets (similar effect is present in the OSISAF dataset). We only assimilate sea ice concentration when some ice is present in the neXtSIM-F previous forecast, or in the Topaz previous forecast.

3) the thin ice (below 20 cm for AMSR2) is seen as open water (see figure 1) by microwave satellite sensors. This effect is well known but rarely taken into account. Based on results from the ESA CCI project some of us have been involved in, we take this effect into account in the data assimilation system by defining an AMSR2-like concentration estimate based on the modelled ice thickness and concentration.

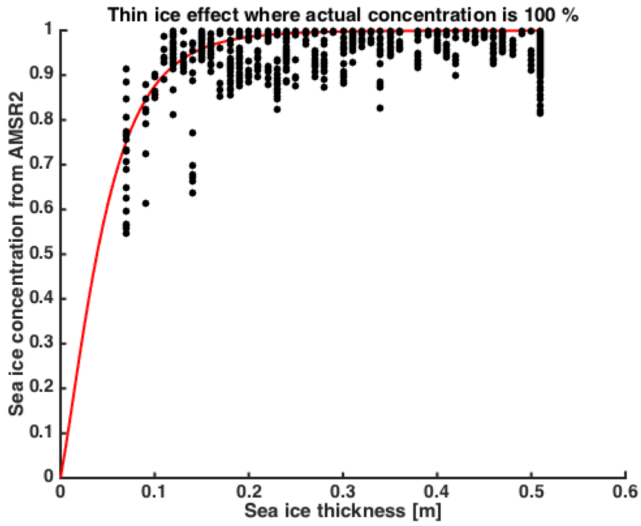


Figure 1: The thin ice effect makes the micro-wave based concentration products indicate low concentration when it is actually 100% concentration. Here is an example from the ESA CCI project for the AMSR-2 sea ice concentration.

The OSISAF ice concentration was proposed as an alternative to the AMSR2 ice concentration data. However, OSISAF is also based on a microwave sensor and then also suffers from the same biases as the AMSR2 data: thin ice effect, effect of the melt ponds… OSISAF is less sensitive to weather noise than AMSR2 data but this problem is well treated by the solution described here above. In consequence, we found there is no added-value to include the OSISAF concentration in the system. However, a new version of OSISAF based on AMSR2 is available since a few months and could be used to replace the AMSR2 data from Hamburg. This new version is based on a joint effort from the remote sensing community to select the best algorithms for deriving sea ice concentration from satellite data.

The CryoSAT data was also proposed but finally not included in the system for the following reasons:

- The Kara region has a poor daily coverage (see Figure 2). Only a few tracks per day are available.
- The uncertainties on the estimated thickness, which are mostly depending on assumptions (because poorly observed) on the local snow depth and snow and ice densities, are extremely large and not documented for the Kara Sea regions. Only some partial evaluations are available for the multiyear ice north of Greenland and in the Beaufort Sea, using the ice thickness measurements from the NASA IceBridge flights.

For these reason, we think it was not worth trying to use the CryoSat data at this stage, and this task was not completed.

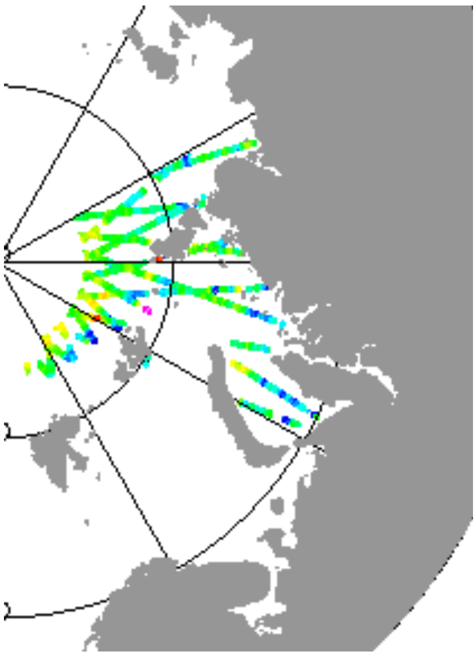


Figure 2: Example of the sea ice thickness products (2-days average around March 7, 2016, on the right) retrieved from CryoSAT by CPOM (http://www.cpom.ucl.ac.uk/csopr/seaice.html) and available operationally during winter months. In summer, the altimeter cannot distinguish melt ponds from open water.

1.1.2 Assimilation method

The assimilation scheme used for neXtSIM-F is a sequential and intermittent assimilation scheme. Before each new forecast (i.e., every day), a simple error blending method is used to define a new model state (called the analysis, in green in the equation below) by combining the background state (in red in the equation below) and observations (in gray in the equation below) as follows:

$$\mathbf{x}_a = \mathbf{x}_b + \underline{g}\left(\underline{k}\left[\mathbf{y} - \underline{h}(\mathbf{x}_b)\right]\right)$$

The new model state is used as initial conditions for the following forecast.

For each assimilated dataset, an observation operator, h, is defined to produce SMOS-like and AMSR-2-like fields from the set of variables defined in the model.
The observation operators,

- ensure the conversion from model variables to observed quantities,
- may be based on averaging and inverse modeling,
- can depend on several model variables.

The backward operators, *g,*

- are roughly the inverse of the observation operators,
- interpolate the corrections onto the model state,
- manage the inter-variable consistencies.

The weights, *k*,

- are based on a-priori estimates of the background and observation error variances as:

$$k = \frac{\sigma_b^2}{\sigma_b^2 + \sigma_o^2}$$

An important assumption we make in neXtSIM-F is that the two types of observations are uncorrelated, and can then be assimilated independently. This assumption is based on the large difference in the size of the footprint and the timescale at which the measured quantities evolve. SMOS gives the mean thickness over a large area and exhibits small day-to-day variations, whereas AMSR2-ASI sees the local sea ice concentration that may vary drastically from one day to the other.

The observation operator for the AMSR-2 concentration is multivariate, meaning that it takes the simulated concentration and thickness into account (i.e., to account for the thin ice effect). There is no spatial averaging as the resolutions of the model and data are similar.

The observation operator for the SMOS thickness is solely based on the simulated sea ice thickness. As SMOS is only valid for area of nearly 100% concentration, it is not assimilated elsewhere.

The backward operators are approximated being inverse operators of the observation operators. In neXtSIM-F, the backward operators are mono-variate even if the observation operators are not. The assimilation of SMOS then only affects the simulated thickness and the assimilation of AMSR-2 concentration only affects the simulated concentration.

1.2 Technical improvements to the forecasting platform neXtSIM-F

1.2.1 Increase code efficiency by switching from Matlab to C (partial in-kind)

The neXtSIM model (neXtSIM acronym stands for "*neXt generation Sea Ice Model*) proposes an alternative to classical Eulerian or purely discrete sea ice models. In neXtSIM, the Elasto-Brittle rheology causes a strong localization of the deformation, mimicking the formation of linear kinematics features, that are also seen from space. The localized deformation events generate discontinuities in the sea ice model fields (concentration, thickness and velocities) at the scale of the resolution. These discontinuities are remarkably well preserved (i.e. with very few diffusion effect) over time by the purely Lagrangian advection scheme (see Figure 3).

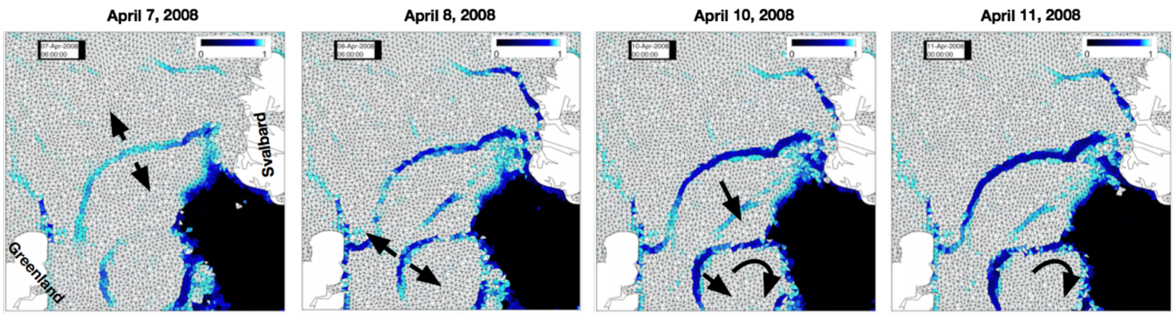


Figure 3: Example of sea ice concentration fields at Fram Strait and the underlying moving mesh coming from a one-year simulation using neXtSIM in a full Arctic configuration and with a resolution of about 10 km.

The first version of neXtSIM used for the early stage of the Kara project was implemented in Matlab and based on external libraries for the numerical solver (cholmod) and the mesh adaptation (BAMG). This version was efficient enough for regional setups at 5 kilometers and Arctic setups at 10 kilometers. For larger setups, using MPI parallelization is necessary due to the size of the system to solve.

A C++ version of the neXtSIM model has therefore been developed in parallel to the Kara project by the postdoc Abdoulaye Samaké and is now the one used for the neXtSIM-F platform. The advantages compared to using the previous version in Matlab are the following:

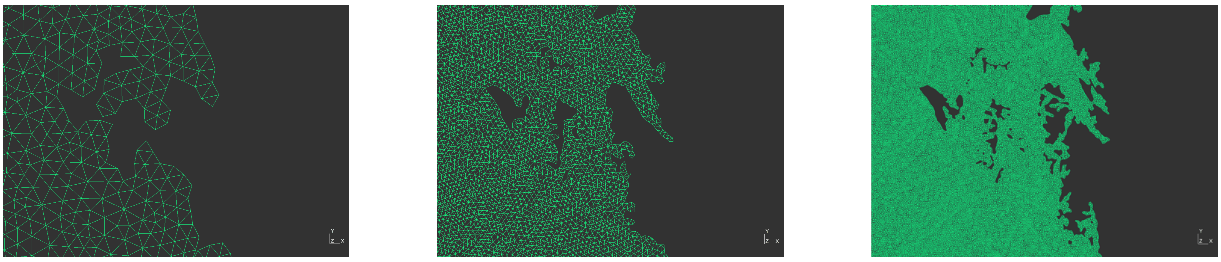
- **Efficiency**
  - The code can run in parallel by using both OpenMP and MPI (Samaké et al, 2017).
  - The code can handle much bigger meshes, enabling the use of higher resolution and larger domain.
- **Flexibility**
  - The code can run on clusters, as well as on personal computers.
  - The code uses well-known and free libraries (Gmsh, Metis/Chaco, PETSc, Boost,...).

- The code is easier to couple to other components (e.g. wave models, ocean models, atmospheric models, 1D physics from LIM or CICE,...).

The scripts managing the launch of the forecast, the data assimilation and the automated evaluation have been adapted to the new C++ code. We note that the C++ version of the model running on one single core and the adapted scripts have been used for the work presented in the second part of this report.

1.2.2 Increase the coastlines accuracy of the Barents/Kara model domain

We used an algorithm written by the developers of the Gmsh mesher (http://gmsh.info) to automatically define a coastline that is as precise as the model resolution (see Figure 4). The very small features such as small islands that will not be represented by the coastlines will still play a role in the sea ice dynamical response through the ice-grounding parameterization included in neXtSIM two years ago and based on the work of Lemieux et al. (2015). The source data are from the gshhs coastlines database[1].



10 km 3 km 1 km

Figure 4: Details of the coastlines and meshes obtained at different resolution (10, 3 and 1 km) by the unref meshing tools.

1.2.3 Physics improvements of the forecasting platform neXtSIM-F

We checked that the drag parameters tuned in the study of Rampal et al. (2016) for the ERA interim atmospheric reanalysis being used as forcing were also the best to use for in neXtSIM-F when using the ECMWF atmospheric forecasts as forcing. This is probably because the ECMWF atmospheric forecast is obtained with the same model as the one used for producing the ERA interim reanalysis.

An important conclusion from Rampal et al. (2016) is that the RMSE in the simulated ice drift can be largely reduced by using atmospheric forcing with higher resolution. Using such an atmospheric forecast is therefore one option to improve the ice drift forecast.

1.2.4 Implementation of the Maxwell-Elasto-Brittle rheology

[1] https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html

This point was not in the list of tasks proposed for the one-year extension, but as it is based on the work of Véronique Dansereau whose thesis was supported by Total, we think it should be mentioned here. The implementation of the Maxwell-EB rheology in neXtSIM is based on Dansereau et al. (2016) by adding a relaxation term to the evolution equation of the internal stress. This relaxation term is active when the ice is damaged, so that the internal stress rapidly decreases, allowing large deformation to occur. The Maxwell-EB rheology is used for the case presented in part 2 of this report, and also for a paper to be soon submitted to *The Cryosphere* journal on the spatial and temporal scaling laws of sea ice deformation (Bouillon et al., 2017).

2. Forecast evaluation

2.1 Automated evaluation against near real-time satellite-derived products with good spatial coverage

As in the phase 1 of the Kara Sea project (see the final report, NERSC report number 369), the operational forecasts were evaluated *on-the-fly* during the whole running period (November 2016-June 2017). The forecasted drift, concentration and thickness were validated against the

- low-resolution OSISAF drift provided by MET Norway (http://osisaf.met.no/p/ice/lr_ice_drift.html),
- AMSR2 ice concentration provided by the university of Hamburg,
- SMOS ice thickness provided by the University of Hamburg (http://icdc.zmaw.de/1/daten/cryosphere/l3c-smos-sit.html).

The automated evaluations were available on a daily basis on a FTP server, as mentioned on the product webpage https://nextsim.nersc.no.

2.2 Evaluation dedicated to specific processes

2.2.1 Comparison to high resolution sea ice drift and deformation data

Deformation is defined from the spatial derivatives of the sea ice drift and depends on the specified spatial and temporal scales of observation. Thanks to its high spatial (~10 km) and temporal (~1-2 days) resolutions, the high resolution sea ice drift product available in near real-time through the Copernicus Marine Environment Monitoring Service (CMEMS) is a good starting point to quantify local sea ice deformation that strongly affects the ice cover state by opening and closing leads and forming ridges. However, by performing a preliminary feasibility study using sea ice drift fields from the CMEMS portal (see an example in Figure 5 showing the x and y-velocity components used to derive deformation seen on Figure 6), we determined that some adaptations are required before it can be used to evaluate the sea ice drift and deformation produced by the neXtSIM model.

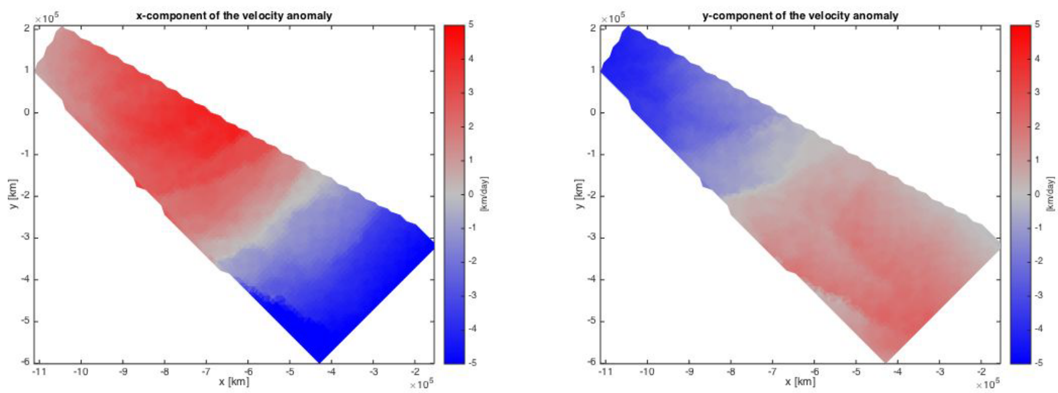


Figure 5: Example of sea ice velocity anomaly fields for a 800 by 800 km region north of the Canadian Arctic Archipelago. These data are taken directly from a file[2] provided through CMEMS portal and are computed after resampling the ENVISAT SAR images to a resolution of 300 m.

The computation of sea ice deformation is indeed strongly sensitive to noise in the sea ice motion fields. Quantifying this noise is not straightforward, as its signature may be similar to real small-scale motion of sea ice, especially in the marginal ice zone. From the preliminary study, we identified that the main source of the noise is the quantification error coming from the resampling of the SAR images. When using 100 m instead of 300 m, the noise is reduced by a factor 3, and the artificial deformation due to that noise is reduced to less than 1% per day (see Figure 6).

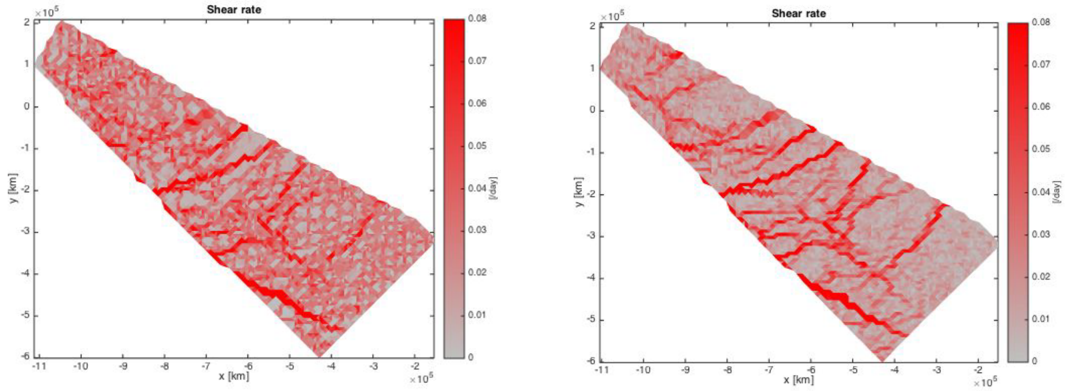


Figure 6: Example of sea ice shear rate fields computed at 10 km resolution from the sea ice drift fields shown in Figure 5. The deformation in the left panel is derived from the original drift data obtained after resampling the SAR images to a 300 m resolution, whereas the right panel shows deformation derived from a dedicated drift dataset obtained after a second searching step based on the 100 m resolution images.

We conclude that for now the high resolution drift products from the CMEMS are too noisy and cannot be used to evaluate the quality of the deformation simulated by the neXtSIM-F platform. We submitted a proposal to the EU-Copernicus program CMEMS in collaboration with our colleagues from the Danish Technology Institute (DTU) to improve the accuracy of the near real-time sea ice drift fields produced from the SAR images of the Sentinel satellites (1a and 1b), but our proposition has not been selected.

Not having such data operationally is not an issue for the present project. The dedicated evaluation of the drift and deformation simulated by neXtSIM, has instead been performed on hindcast simulations and using the RGPS datasets as we did in Bouillon and Rampal (2015) and Rampal et al. (2016), as well as using a lead fraction dataset. Two new papers related to sea ice deformation and lead fraction in

[2] ice_drift_polstereo_wsm_envisat_north_20100309205105-20100310220107.nc

neXtSIM are in preparation (Bouillon et al. 2017 and Olason et al., 2017). Both studies confirm the unique performance of the neXtSIM model at simulating correctly sea ice drift and deformation.

2.2.2 Simulated sea ice thickness fields will be compared to CryoSat along-track thickness measurements

Another way to validate a sea ice modelling system is to look at the seasonal evolution of large scale quantities such as the sea ice extent and volume. Such analyses were performed on hindcast simulations of the neXtSIM model forced with atmospheric and oceanic reanalysis and showed that both the sea ice extent and volume remain in the error bars of the observations, even after several years. These metrics are integrated metrics that characterize the combined effect of different dynamical and thermo-dynamical processes.

A second important check concerns the spatial distribution of the sea ice thickness which is often not well reproduced by sea ice models. The TOPAZ reanalysis, for example, exhibits too small spatial gradients and overestimates the thickness for the central pack and underestimates the thickness near the Canadian Arctic Archipelago. This deficiency is shared with other sea ice modelling systems. neXtSIM though does not show such deficiency and is able to reproduce correctly the large-scale gradient of sea ice thickness, with values of about 5-6 meters along the Canadian Archipelago, and of about 3 meters in the center of the Arctic basin, as in the observations (see Figure 7). As the thermodynamics model in neXtSIM is basically the same as in the classical sea ice models, the relatively good representation of the thickness gradients must come from the better representation of the dynamical processes, especially sea ice deformation and drift.

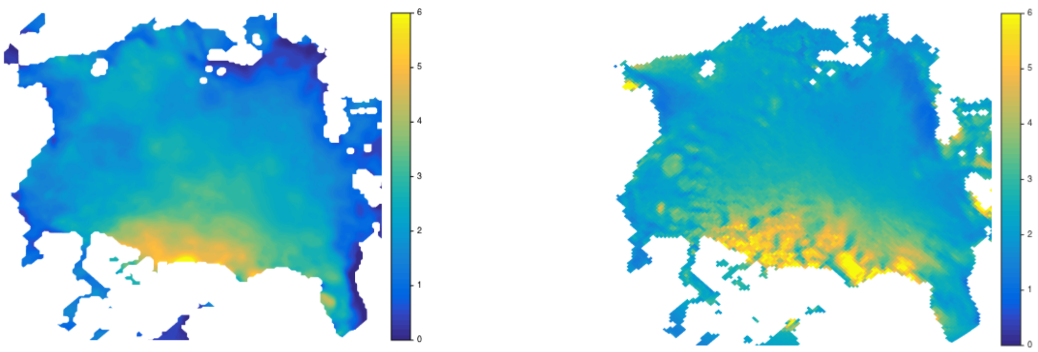


Figure 7: Observed (left) and simulated (right) sea ice thickness for the week 7 April to 13 April 2014. The observations are from the merged CryoSAT-SMOS product delivered by AWI (Ricker et al., 2017). The simulated field comes from a hindcast simulation started from 2011-11-10. At this particular date, and after 3 years of integration, the simulated ice volume is almost identical to the one observed.

3. Forecast dissemination

The dissemination to end-users has been substantially improved and now meets the usual requirements of a typical operational forecasting platform. The improved dissemination channel is based on 3 important tools:

- A dedicated website
  - The website contains 3 sections:
    - a brief description of the platform,
    - an interactive browser to access forecast figures (see Figure 8),
    - the contact information.

  - The website is interactive: one can select the date and the forecast period and directly see the forecasted fields.
  - The website is cross-platform and flexible: it is adapted to be optimal when browsing from a mobile device.

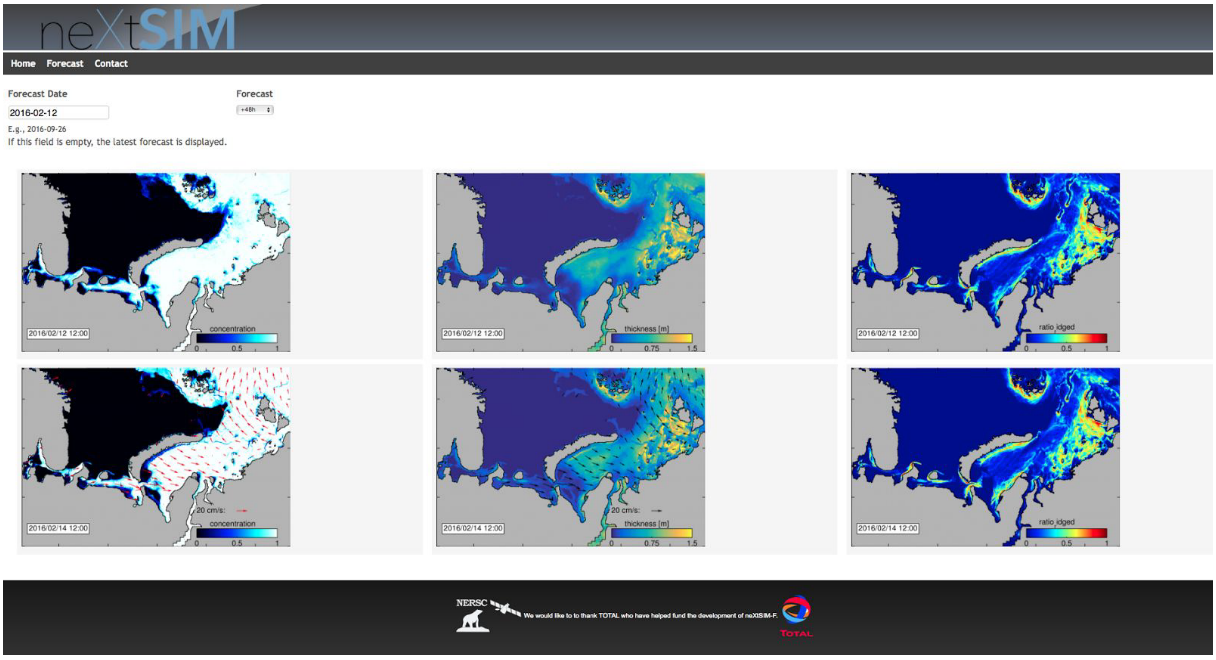


Figure 8: Example of the visual presentation of the neXtSIM-F forecast on the new interactive website.

- A Thredds server and a FTP server
  - Users can access the data through a Thredds catalog or directly on a FTP server.
  - The Thredds catalog provides:
    - a formatted and complete description of the data,
    - access to the data through OPENDAP and WMS,

        - access to viewers (Godiva, Java ToolsUI and Integrated Data Viewer).
    - The Thredds server is the same as the one developed for the SWARP EU project, for which the dissemination through the NAVTOR software was demonstrated.

- Outputs in the netcdf format
    - The C++ code produces output in the netcdf format.
    - The outputs are netCDF 4 files compliant with the CF convention (version 1.6).
    - The variable names follow the CMOR (CMIP5) convention.

4. Other relevant activities:

Sylvain Bouillon was **lecturer** to the international GODAE school, on operational oceanography, Mallorca, October 2017
Pierre Rampal is **invited** to the AGU Fall meeting (San Francisco, ~24000 attendees). A poster was also presenting our activities on sea ice forecasting.
Sylvain Bouillon was **invited speaker** to the ECMWF Annual Seminar on "Earth system modelling for seamless prediction", http://www.ecmwf.int/en/annual-seminar-2016, Reading, UK, September 2016.
Sylvain Bouillon was **invited speaker** to the IRDR Total Ice Seminar on "Ice action on structures and ice rheology description in ice dynamics models", London, UK, June 2016.

PART 2: A successful use of neXtSIM-F for planning and routing of the SHOM vessel in the Greenland Sea in August 2017.

Most of the operators working in ice-infested waters rely on near-real-time data acquired from satellites and distributed directly as SAR images or indirectly as ice charts. One way to convince those "clients" to use model forecast outputs is to show *a posteriori* that the information we provided at a given time *t* for the next days were in better agreement with the corresponding information observed during those days, than when comparing to the information available at time *t*. In other word, we have to prove that we beat the persistency of their preferred source of near-real-time data.

Forecasting SAR-like data is probably still in the domain of science-fiction, as one would need to use very high resolution systems (of the order of 10 meters). On the contrary, forecasting ice charts-like maps should be achievable with existing systems. Ice charts usually cover regional or Arctic wide domains and provide on a daily basis information on the ice concentration for the day before. The production of ice charts is made by sea ice analysts who combine data from various sources (SAR images, passive microwave satellite data, in-situ observations, forecast systems, …) in order to provide maps of ice classes.

Usually operational sea ice forecasts are not based on ice charts but directly on passive microwave satellite data providing estimates of sea ice concentration at resolution of about 5-20 kilometers on a daily basis. However, these data are indirect measurements of sea ice concentration, and are subject to well known biases. As described above, these data usually perform badly when ice ponds are present, for thin ice, for highly fragmented and low concentration ice, and near the ice edge. Building a system taking all these limitations into account is feasible, but not yet achieved. Another solution is to directly assimilate ice charts that are also provided on a daily basis and are known to have less persistent bias.

The Greenland Sea neXtSIM-F setup

In July this year, we were contacted by SHOM (French Navy) who asked us whether we could provide real-time sea ice forecast over the Greenland Sea during a couple of days corresponding to a scientific campaign from mid to end of August 2017. It was a good opportunity to test "in real conditions" the capability of the forecasting platform and get feedbacks during and after the cruise. We therefore built a new setup for their region of interest and implemented a scheme to assimilate the ice charts from the US National Ice Center (NIC).

The setup presented here covers the Greenland Sea and Fram Strait and provides every day a 7-days sea ice forecast at a resolution of 10 km (see Figure 9). The initial forecast conditions are computed by assimilating sea ice concentration from the daily and weekly ice charts produced by the U.S. National Ice Center (NIC) into the model state as given by the previous forecast. The model is forced with ECMWF and ARCMFC (TOPAZ) forecasts for the atmosphere and ocean, respectively.

The products delivered every day at 3 a.m. on a FTP server were:

- Maps (see Figure 9): for days -1, 0, +1, +3, +6

  The concentration maps use the color code from the Norwegian ice charts.

  The ice thickness maps use the ice breaker classification of Bureau Veritas.

  Ice drift are instantaneous drift at noon.

- Netcdf:

  Daily outputs of concentration, thickness and east-west velocities, in a netcdf file.

Assimilation of the NIC ice charts

By comparing results from the Greenland Sea setup assimilating the AMSR2 and OSISAF ice concentration to ice charts and SAR images as those available on www.polarview.aq/arctic, we realized that, at this period of the year (Summer), the zone of interest (Greenland Sea) is largely covered by low concentration which is badly or even not at all represented in satellite-derived concentration products such as OSISAF and AMSR2. With the initial setup that only assimilates those products, we could then be quite far from reality. To improve that point, we modified the neXtSIM-F system to automatically download the NIC ice charts (http://www.natice.noaa.gov/Main_Products.htm), translate them into a readable format for our model and incorporate them into the data assimilation scheme. The daily NIC ice charts contain 3 categories, for ice concentration below 0.1, between 0.1 and 0.8 and between 0.8 and 1 (see http://www.natice.noaa.gov/daily_graphics.htm). The weekly ice charts contain many more

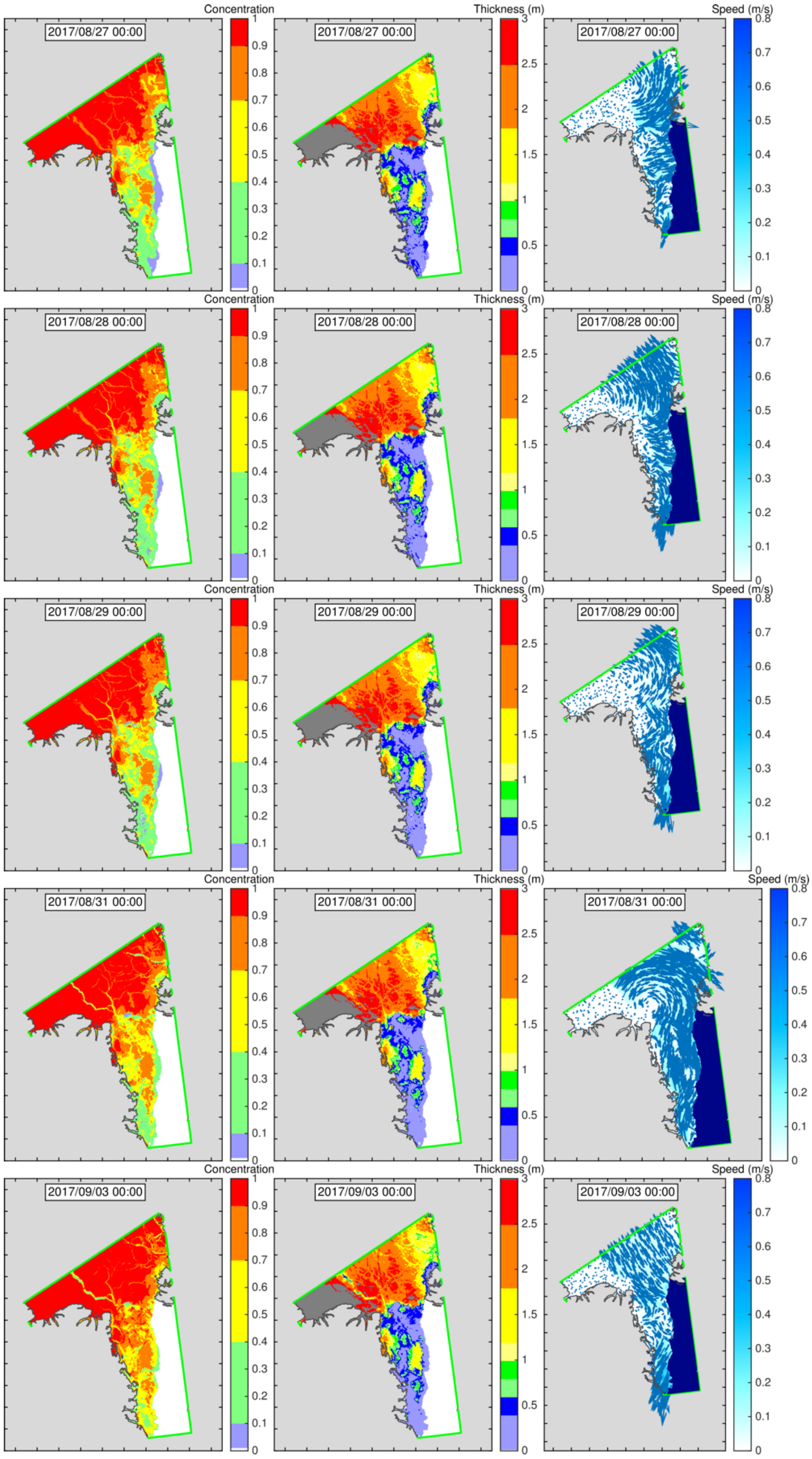


Figure 9: Examples of sea ice concentration, thickness and velocity forecasted for the Greenland Sea and Fram Strait for the T-1d, +0d, +1d, +3d and +6d time horizons in August 2017. Plotted ice drift vectors are instantaneous drift at noon of that day.

categories (see Figure 10), typically [no ice, 0-0.1, 0.1-0.4, 0.4-0.6, 0.6-0.8, 0.8-1, 1] (see http://www.natice.noaa.gov/images/weekly_arctic_con.png). Both are available in near-real-time (about one-day delay) for the whole Arctic. Another option would be to use the Norwegian ice charts, but those are only available for week day, and not over the whole Arctic (see polarview.met.no/regs/general_20170727.png). Both the NIC and NIS ice charts were considered as state of the art in the report of Pastusiak (2016, TransNav) on the use of satellite-based data for navigating in the Arctic.

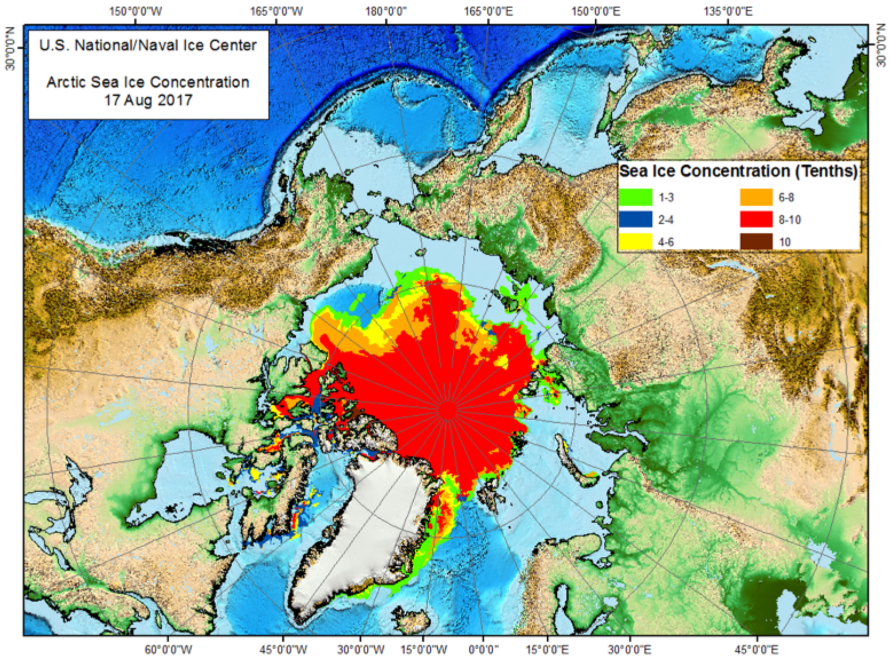


Figure 10: Multi-classes weekly ice charts from the US National Ice Center.

Use of the forecast for route planning

The netcdf and maps were used for planning during the expedition (see Figure 11). Our forecasts indicated that the location for the main mooring experiment would not be free of ice on time for the mission. Based on that information the team modified their plan and went to Jan Mayen Island instead before trying to come back West.

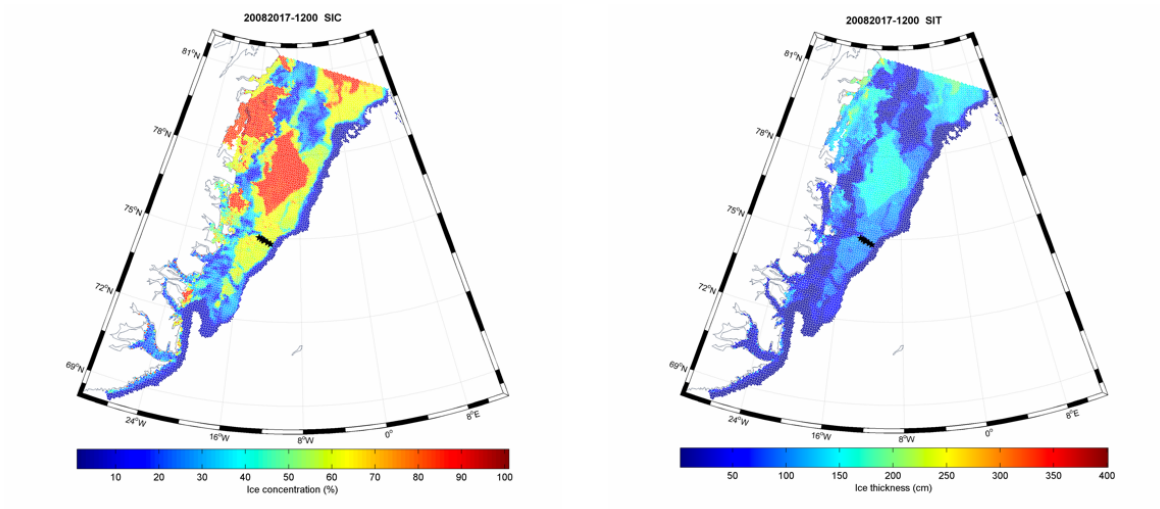


Figure 11: Forecasted sea ice concentration and thickness for the Greenland Sea setup. The black crosses indicate the favorite location for the main experience of the SHOM scientific campaign.

<u>Use for navigating in ice-infested areas</u>

At the end of the mission, the vessel went West but was stopped by a band of ice seen on the forecasts as well as on SAR images. Based on our information (see Figure 12), they tried to go around that band by navigating South but they had to give up and leave the area because of the fog.

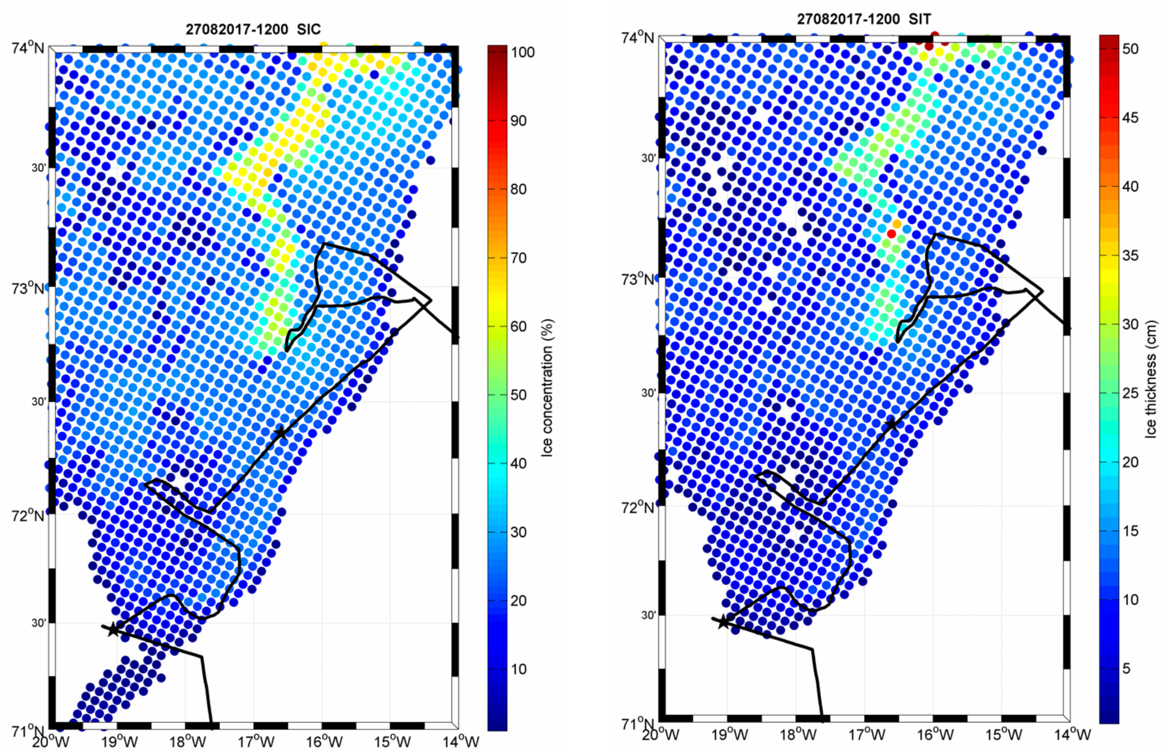


Figure 12: Forecasted sea ice concentration and thickness fields integrated in the navigation system of the vessel and used for navigation in ice infested areas

<u>SHOM report on the use of neXtSIM ice forecasts during the Narval Hydro 2017 mission.</u>

The feedbacks from the people of SHOM were very positive. The conclusions of their report are: “The **neXtSIM forecasts have revealed precious insights in order to plan our cruise** specially to estimate how the situation will evolve in next days. They were reliable with some uncertainties, position of the ice-free water limit (0%) was well represented but with a 45-75km eastern offset. We noticed that they tend to be more pessimistic than our in-situ observations (low concentration predicted areas while in free waters) but can reproduce well ice patterns.”

“The experimentation of the neXtSIM forecasts was very promising. They are closer and closer to the SAR derived ice charts and provide very useful trends. **We can wonder if in the near future, forecasts will be the best estimate to use**: **reliable for ice patterns**, offering an **anticipation ability** comparing to ice charts (5 days trend and visible drift of blocks, interesting in such areas where changes occur in short time delay), **available under bad satellite communication**, **readable for non-specialist** people. Improvements in accuracy within the 0-30% ice concentration zone would help in operational cruising.” (See Figure 13)

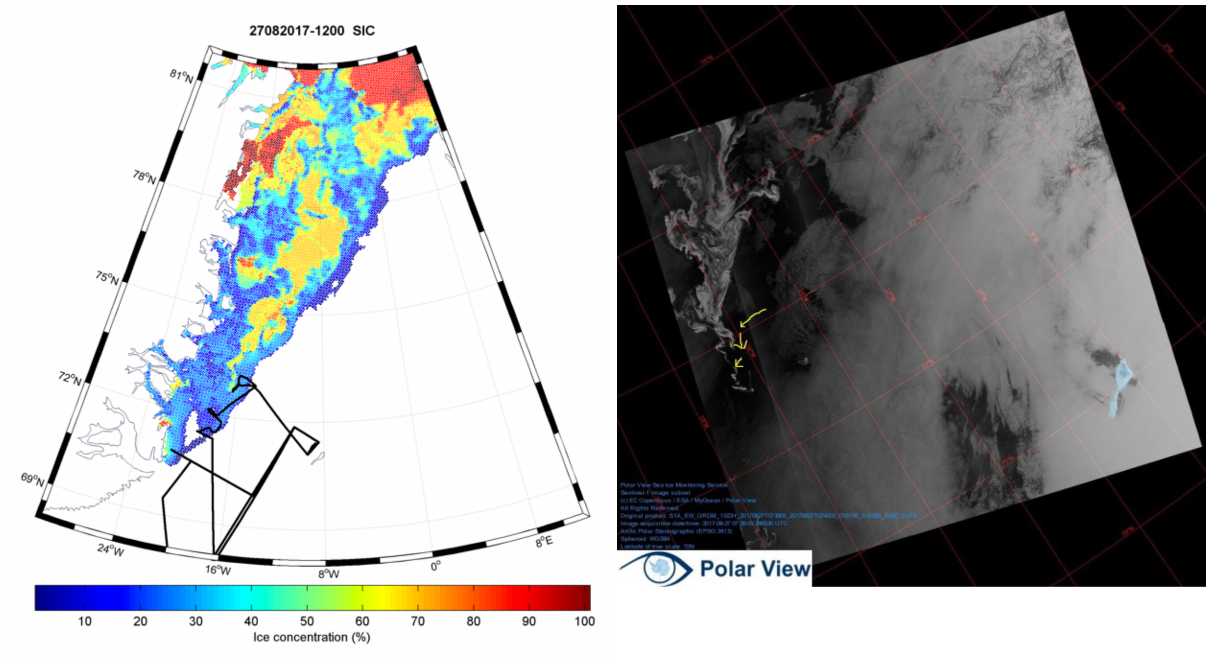


Figure 13: The forecasted sea ice concentration produced by the neXtSIM-F setup for the Greenland Sea was use for planning and navigation in ice-infested areas. The ouputs of the system compares well to the available SAR images, but have the advantage to be always available, to provide anticipation ability, to be easily downloaded on the ship even with limited communication means and to be easily readable for non-specialists.

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