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BETTER SEA ICE FORECASTS FOR THE NORTHERN BALTIC SEA

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FOREWORD

In this report no 133, the Winter Navigation Research Board presents the results of BETTERSNOBAL - Better Sea ice forecasts for the Northern Baltic Sea. Project goal was to improve ice forecasting and to include ice stress calculations by implementing changes to the forecasting model operated by FMI.

The Winter Navigation Research Board warmly thanks the authors for this report.

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BETTERSNOBAL - Better Sea ice forecasts for the Northern Baltic Sea

Final report

Winter Navigation Research Board project W24-2

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Contents

Summary

This project for the Finnish-Swedish Winter Navigation Research Board concentrated on improving ice forecasting in the Baltic Sea by implementing several stakeholder relevant changes to the operational ice forecasting model operated by the Finnish Meteorological Institute (FMI).

The main changes involved updating FMI's NEMO-based ocean forecasting system, including a newer version of the coupled sea ice model SI3. The system is now also capable of calculating ice stresses. Furthermore, we identified other areas of the forecast to be improved in future projects.

Introduction

In the Baltic Sea area, numerical deterministic forecasts of sea ice are routinely used to simulate the evolution of ice conditions throughout the winter. The users of these forecasts include duty forecasters and winter navigation experts. This is the final report for BETTERSNOBAL, a project for the Finnish-Swedish Winter Navigation Research Board focused on improving ice forecasting in the Baltic Sea by implementing several stakeholder-relevant changes to the operational ice forecasting model operated by the Finnish Meteorological Institute (FMI).

FMI operates two numerical models that could be used to provide ice forecasts.

First, the HELMI model is a well-established 2D sea ice model that focuses on ice dynamics, driven by atmospheric forcing. Though it performs well in forecasting ice deformation and lead opening, it has limited thermodynamic skill and is not coupled to an ocean model. The HELMI model was written at FMI but has not been updated for several years. HELMI is a legacy model with limited support and will likely be retired from operational service in the medium term. The HELMI model has been documented in many publications, e.g. Haapala (2005) and Lensu et al. (2013).

Second, the NEMO model is a 3D ocean model that couples sea ice physics with ocean currents and thermodynamics. It is an open-source model in active development by an international community and is the operational 3D ocean model at FMI. The focus of this project was on improving NEMO based sea ice products. In the medium term, NEMO will likely become the main source for FMI's Baltic Sea ice forecast. The NEMO model is documented on a general level by Madec et al. (2023), with Baltic Sea specific information provided by Hordoir et al. (2019) and Kärnä et al. (2021).

During the project, we took several steps to improve sea ice forecasting products at FMI. We implemented an update of the NEMO based forecasting system, that included a new version of NEMO model code. This version included several improvements to the ice model available in the original model code. We adapted the model configuration to run in FMI system and implemented necessary customisations. We performed hindcasts and validated the updated system. Furthermore, we performed tuning experiments to test the updated system.

The project plan laid the following major milestones for the project. First, compression variables were enabled on an experimental basis and hindcasts were performed (milestone M1). These hindcasts were validated (M6). Then, based on this work, further improvements were implemented (M9). Finally, the final report was submitted (M10, this report). These steps are documented in this report.

FMI's sea ice forecast production

FMI produces sea ice forecasts within the same production system as its other operational products. This ensures that the production process is monitored, and that the quality of the process is consistent.

At the time of writing, the coupled NEMO-SI3 ocean-sea ice model is operationally run at the FMI four times a day. It provides forecasts of both ocean physics and sea ice. Forecasts are produced for several

2D and 3D ocean variables, including sea level, temperature, salinity, and current velocity. Sea ice products include ice concentration, thickness and ice movement. The sea ice forecast from the NEMO system is in preoperational testing and is not disseminated for end users. The operational sea ice forecast originates instead from the HELMI model system. HELMI is run four times a day during ice winter.

At the start of the project, the NEMO based forecasting system was built on NEMO-SI3 version 4.0. During the project, this was updated to version 4.2.1. of the NEMO source code. This version of the code was based on the NEMO-Nordic setup, as used in the Copernicus Marine Service Baltic Sea forecasting centre (Baltic Sea Physics Analysis and Forecast; https://doi.org/10.48670/moi-00010). Thus, our updated system code incorporated the improvements made to the NEMO-Nordic code, including fixes backported from NEMO version 4.2.2. The model domain covers the combined Baltic Sea-North Sea area on a 1 NM (nautical mile) resolution grid, though only the Baltic Sea part of the domain is delivered for forecasting purposes. The model is forced with data from the MEPS atmospheric forecast (66 h forecast), supplemented by ECMWF data (next 54 hours). Boundary conditions for the open border in the North Sea are fetched from the Copernicus Marine Service North-West shelf product (Atlantic - European North West Shelf - Ocean Physics Analysis and Forecast; https://doi.org/10.48670/moi-00054).

Results

Analysis of development needs for the ice forecasting system

There are two main categories of users for FMI's ice forecast products. First, there are external users, who take advantage of either customised products or open data provided by FMI. Second, there are internal users at FMI, most notably the duty forecasters located at the Oceanographic Services of the institute. In this project, we prioritized the needs of these internal users. To understand their specific requirements for ice forecasts, we organized internal meetings at FMI, and we discussed the process of forecasting on multiple occasions with these users. Additionally, we supplemented this information with information received from external users regarding ice forecasting, obtained during discussions that took place as part of our routine interactions with such users.

At the outset of the project, we conducted an initial analysis of development needs. We then updated this analysis with information from users, also taking into account the model validation results from the project as they became available. Here we present a summary of that process. During the project itself, this analysis of development needs helped us to prioritize work; in the future it will continue to be useful when further development work is considered.

Discussions with duty forecasters highlighted the utility of current ice forecasting products for operational activities. Sea ice forecasting experts noted that model data is especially useful when generating forecasts but is less vital for creating ice charts of current circumstances. As the current legacy system is always initialized with current ice chart data, it cannot provide the duty forecasters with new information for ice charts. The current legacy HELMI based ice modelling system is not coupled to a hydrodynamic component, the ice drift is calculated entirely based on wind drift. This means, that an addition of a coupled hydrodynamic component is a notable improvement.

It became quickly apparent in the discussions that there is a need to build further trust in the NEMO based products, which in practice meant that the sea ice component of NEMO would need updates before it could fully replace HELMI. On the other hand, as a legacy system, the support for the HELMI products is minimal at FMI. Furthermore, it is expected that the HELMI based system will be retired relatively soon. Therefore, a version update of the NEMO modelling code was seen as the most critical development need, as it would improve the longevity of the system and enable further development of

FMI's sea ice forecasting products in the long term. We determined this development to have **high priority**.

For ice compression forecasts, sea ice experts felt that having such products would benefit their work and communicated that this has been on their "wish list" for a long time. However, significant possible challenges were identified as far as moving earlier (research-oriented) work to operational practice is concerned. Clearly there is a need to test the product together in sufficient extent. The process of introducing a new forecast product introduces risks if the features of the forecast product are not sufficiently well understood. Furthermore, based on previous research on the topic, it can be expected that several practical issues need to be resolved before operationalisation. Therefore, we determined this development to have **medium priority** with a) an aim of taking at least some steps forward towards eventually achieving this goal and b) an emphasis on ensuring sufficient opportunities for testing.

Another point highlighted during this discussion was that, unlike the legacy HELMI system, the new NEMO-based system maintains its state between forecasts, rather than being re-initialized with ice chart information before each cycle. This is a significant difference, with the drawback that the state of the NEMO-based system has the potential to deviate substantially from reality during the winter. For this reason, the users noted that data assimilation from observations would be useful.

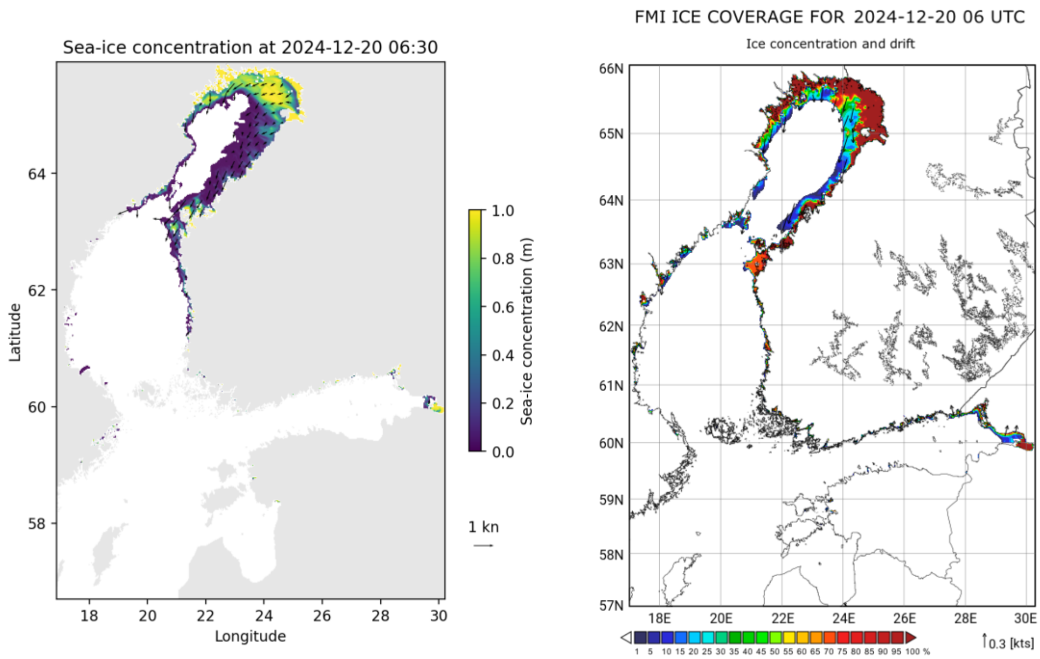

Figure 1. Prototype product showing NEMO sea ice concentration on 20 December 2024 (left). Legacy HELMI based concentration product for the same date (right). Note the differing scales.

Currently, the FMI forecasting system includes data assimilation only in the atmospheric component, such that observations influence marine/sea ice forecasts only indirectly. While this is sufficient to keep the state of the model reasonably close to reality, there can still be differences between reality and the model when it comes to important model outputs such as the location of the ice edge. Therefore, for ice forecasting purposes the use of direct (marine/sea ice) data assimilation might be beneficial. Ultimately this development was not determined to be as critical as the update of the forecasting model configuration. It was also noted that successful implementation of the data assimilation system into production is a task that would likely prove too large for the project at hand. For these reasons, we determined data assimilation to have **low priority** in the context of this project - whilst accepting that in the long-term the use of data assimilation may have higher priority.

One potential improvement that was not extensively discussed with users was the fast ice parameterisation. Nonetheless, the developers of FMI's ice forecasting system have identified this as a possible area requiring development work. The legacy HELMI system handles fast ice in a qualitatively different manner from the NEMO system, so it is useful to check how well NEMO performs in this regard. We determined the investigation of fast ice parameterisations to have **medium priority**.

The users did not prioritize ice volume tuning. After discussion, the consensus was, that while these results are often biased in ice models, and it would thus be desirable to improve them, the ice volume is less important for ice forecasting. Therefore, we determined these improvements to have **low priority**.

It became clear during discussions that, due to technical restrictions in FMI's production system, the testing of new products with internal users is somewhat difficult. As major changes to the whole production system are beyond the scope of a research project such as ours, we decided to concentrate instead on updating and modernizing an existing internal web service that allows the internal users to evaluate pre-operational forecasts. We determined that this task, although technical in nature, should have **high priority**, as improvements in this area would facilitate other developments. An example of the prototype product from the new web page, alongside the legacy product, is provided in Figure 1. As this is a prototype product, its appearance may significantly change during further development.

Implementation of the updated forecasting system

An important part of the project was the implementation of a new and improved version of the coupled ocean-ice forecasting system NEMO at FMI. We built the new system using the NEMO code version used in the Copernicus Marine Service Baltic Forecasting and Monitoring Centre. Our main tasks involved adapting this model version to FMI's operational system and testing the system as a whole. This work included a major update in the model code from version 4.0 to version 4.2.1, such that our new system benefits from several improvements to the ice forecasting component of the system. This code version is available online (SMHI et al., 2024).

We then performed two hindcasts in order to gain a better understanding of the model's strengths and weaknesses for ice forecasting purposes. The hindcasts covered ice winters 2010-2011 and 2023-2024. The results of the validation are detailed next.

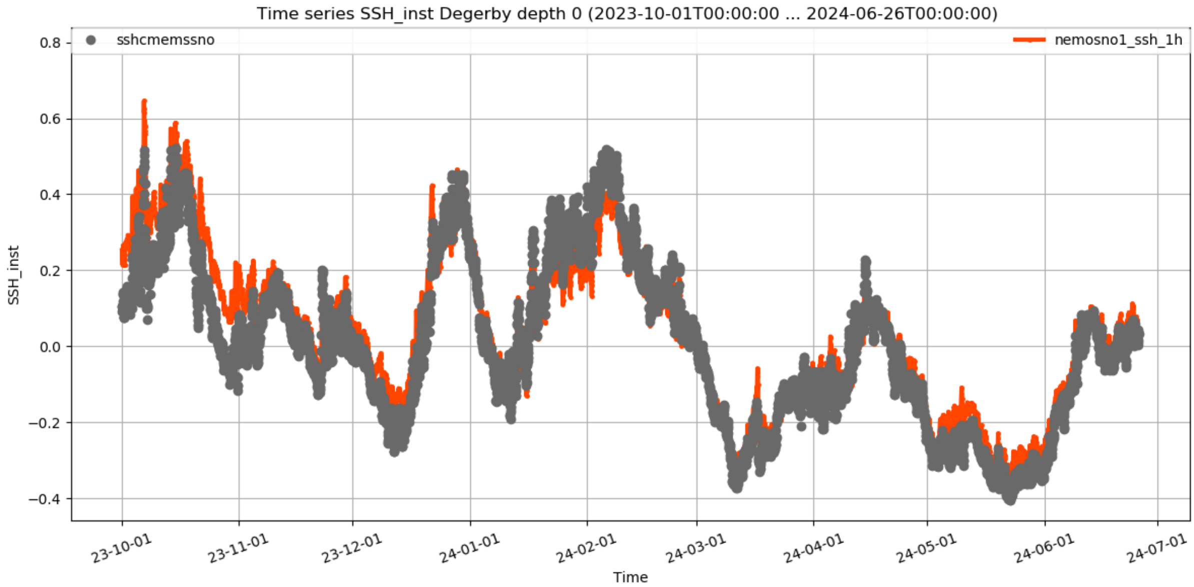

Figure 2. Sea surface height at Föglö Degerby station in the Åland islands 2023-2024. Black line tide gauge observations, red line NEMO model.

Validation of the ocean model component

First, we performed basic validation of the ocean component of the system to check that the model functioned as expected. The Copernicus Marine Service has already carried out extensive validation of their version of the forecasting system. For the purposes of this project, we carried out a limited additional validation of the system to ensure that the performance of our model system was generally on a similar level as theirs.

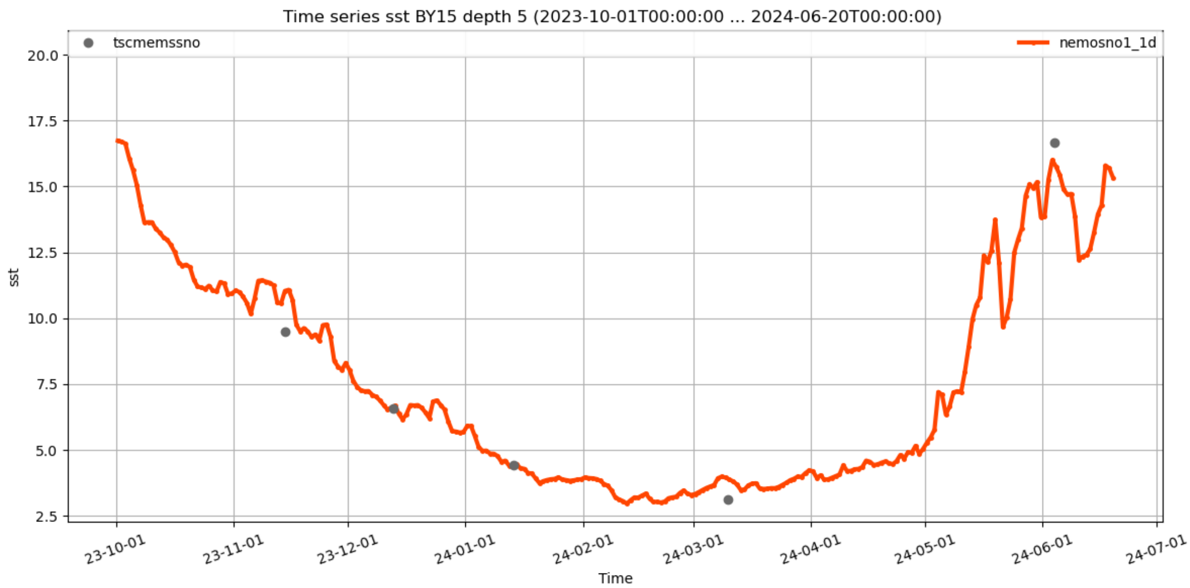

Figure 3. Sea temperature at point BY15 in Baltic Sea Proper in 2023-2024 at 5 m depth. Gray dots are CTD observations.

We validated sea surface height, temperatures and salinities. We discuss here two examples of typical results.

Water level forecasts showed good agreement with observations. For an example, see Figure 2 where comparison between tide gauge measurements at Föglö Degerby station and model results are shown.

Validation of sea surface height is often used to get a general understanding of model's ability to reproduce barotropic dynamics. Overall, the model behaved as well as expected.

Temperature and salinity showed results typical for this kind of a system. See Figure 3 for an example of sea temperature near surface at station BY15 during the 2023-2024 hindcast. The observation is from the Copernicus Marine Service. While the number of observations is limited, it is still clear that the model reproduces the seasonal temperature cycle, and that it remains close to observed sea surface temperatures.

Validation of the sea ice model component

Next, we validated the ice component of the forecasting system. The results of sea ice extent validation for 2010-2011 hindcast run are shown in Figure 4. In this Figure, ice area is plotted for ice winter 2010-2011. The observations in this case are sourced from digitized ice charts. The Figure also shows how the definition of ice covered area affects the results. Overall, the agreement with observations is very good. This indicates that large scale sea ice thermodynamics are generally captured well. However, this does not guarantee that smaller scale phenomena are captured effectively.

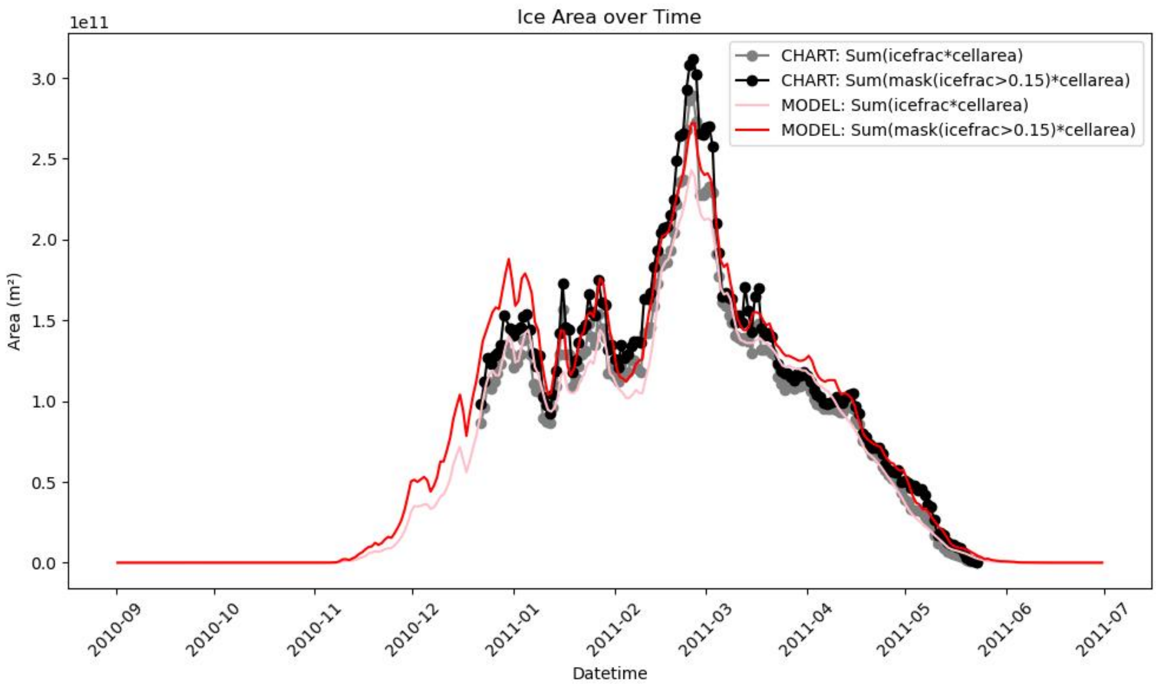

Figure 4. Sea ice area in the Baltic Sea from NEMO and ice chart in 2010-2011. Black and red: sum of all grid cell areas where grid cell is > 15 % ice-covered. Gray and light red are the sum of grid cell areas times their ice-covered fraction.

The most significant differences between the ice chart and the model result occur around late December/early January. In this case the model shows a substantially larger ice area in the Bothnian Sea than the ice chart, possibly overestimating how quickly the area is freezing over (see Figure 5). This difference levels out after a wide freezing event in mid-January, so that on 16 January the model and the chart are already quite close to each other.

Figure 6 shows a comparison of sea ice thickness and in situ measurements from the Finnish coastline in 2024. The in-situ thickness measurements are from manual ice observations. They generally aim to measure a typical thickness, while the model discretizes the ice thickness as a histogram with five bins. To make the comparison as realistic as possible, we chose the thickness of the most common ice

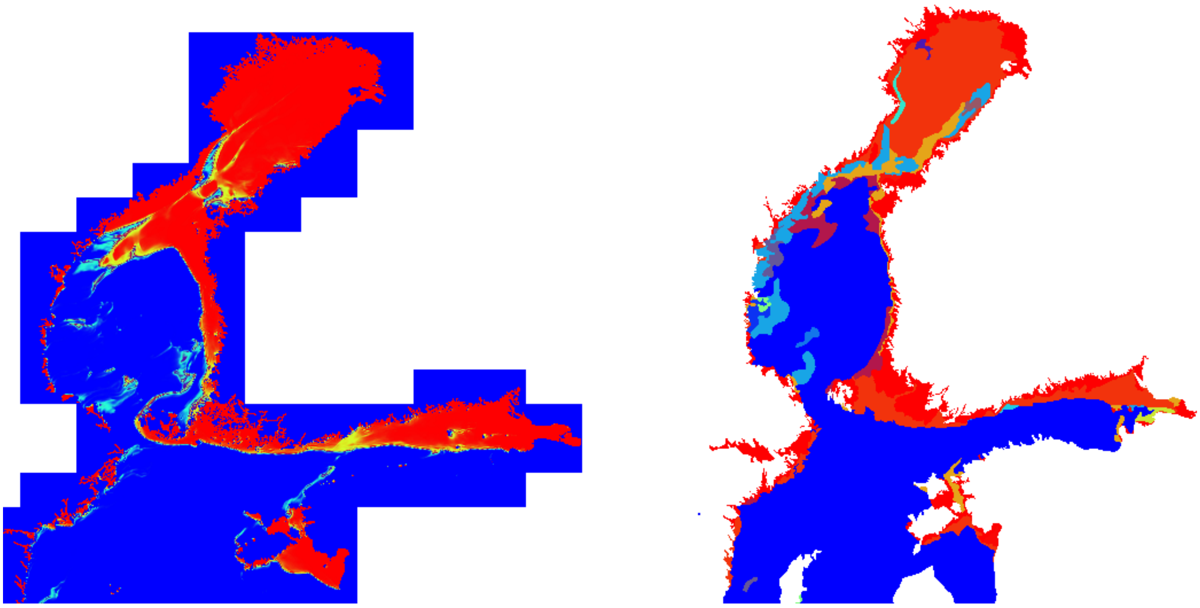

Figure 5. Sea ice concentration in NEMO (left) and ice chart (right) on 13 Jan 2011.

category for comparison. In the Figure model thickness values are roughly grouped in five groups, which is due to this choice. Still, the values in the observations and in the model are not completely comparable. For the model, the values always represent an average over one grid point, while the observation is a point measurement. Taking all of this into consideration, the agreement is reasonable.

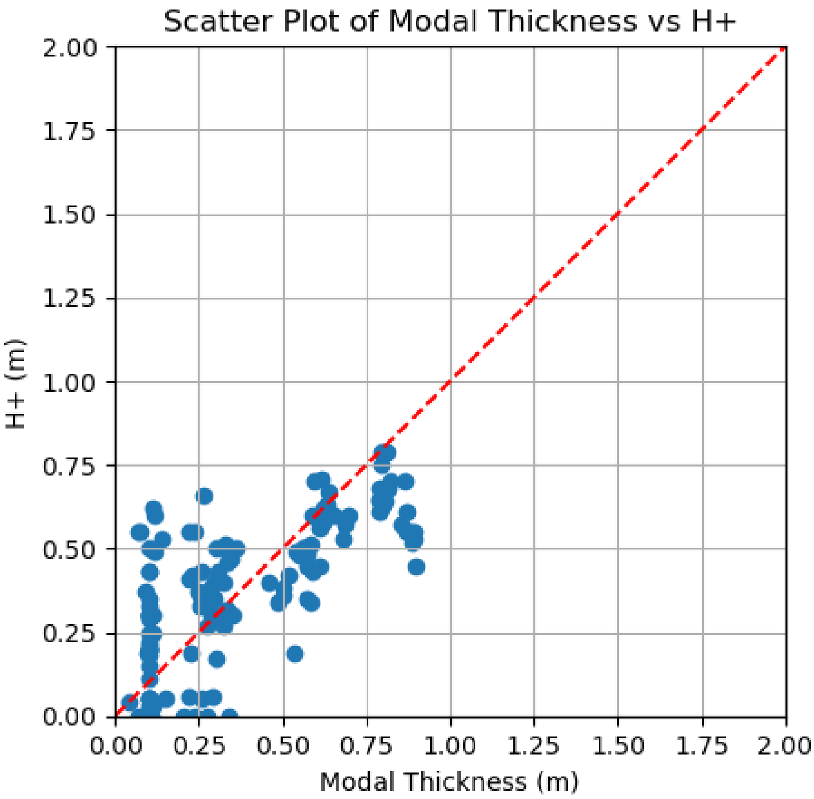

Figure 6. Coastal sea ice thickness for NEMO (horizontal axis) and manual observations (vertical axis) in winter/spring 2024.

Tuning experiments

As noted earlier, tuning of model parameterisations was not prioritized in the analysis and was therefore done only to a somewhat limited extent, with a focus on fast ice parameterisations.

We reviewed several parameterisations available in NEMO for fast ice and selected the ln_landfast_L16 /Lemieux 2016 parameterisation for closer inspection. When we studied the extent of sea ice for winter 2010-2011, we found that the parameterisation for landfast sea ice did not substantially affect the ice area. Figure 7 shows the difference of using the Lemieux parameterisation vs. on not using it. In this case on 13 Jan 2024 there are some notable differences, especially in the Gulf of Finland. If compared to ice chart data, it appears that the use of the fast ice parameterisation in the model gives more realistic predictions of open water areas in the region.

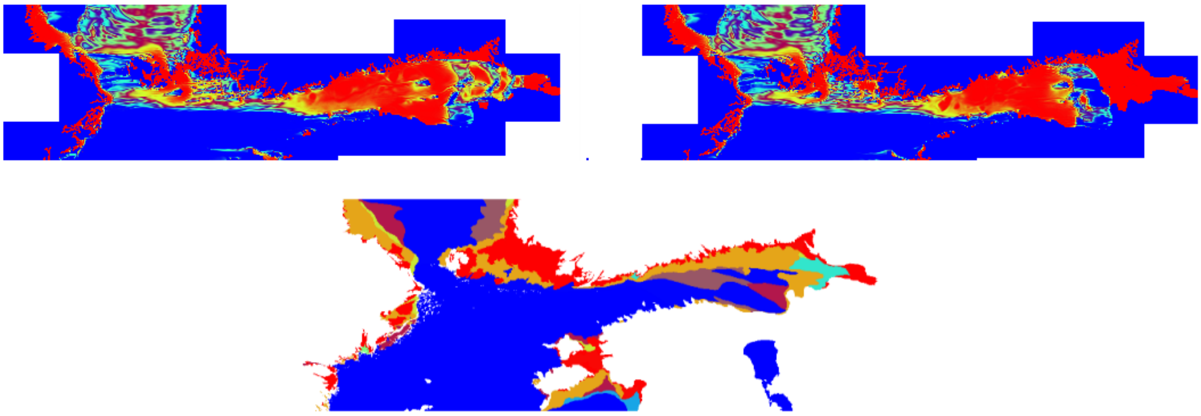

Figure 7. Ice concentration in the NEMO model for the Gulf of Finland area on 13 Jan 2024 without fast ice parameterisation (upper left corner) and with Lemieux parameterisation (upper right corner). For comparison, ice chart data for 14 Jan (lower panel).

Ice compression modelling and products

Ice compression forecasting in the Baltic Sea has been developed in earlier research projects. Most notably, the SAFEWIN project created a prototype of ice compression forecasts for the Baltic Sea. This research has been documented by Eriksson et al. (2009), Lensu et al. (2013) and Eriksson et al. (2015). This work relied on the HELMI model, now considered to be a legacy system. This meant that further development is required to bring these possibilities to the NEMO-SI3 based system.

A significant barrier for full operationalisation is that compression fields can change quickly on short timescales. Simple deterministic forecasts are unlikely to capture rapid changes in the compression fields correctly. Therefore, alternative approaches are required. One option recommended e.g. by Eriksson et al. (2015) is to use ensemble forecasting to produce a risk-based forecast of compressive situations.

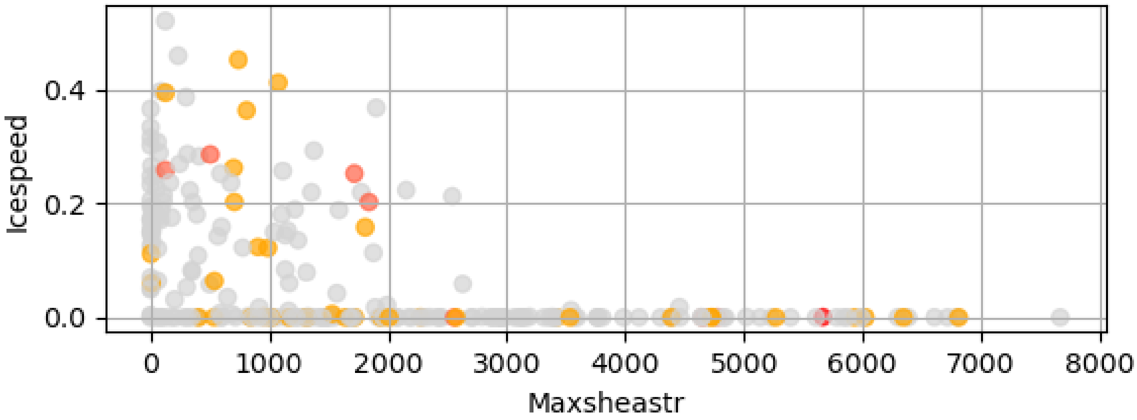

Figure 8. Maximum modelled ice stress during event and mean ice speed during 2024 hindcast. The colour of the dots represents compression reports from ice breakers from grey = no compression to red=heavy compression.

As full ensemble forecasting is computationally very expensive, we decided in this project to start from a deterministic pre-operational compression product, with the understanding that this product would likely not be directly usable, but a first step nevertheless enabling comparisons between compression reports and model data (Figure 8). Then, the options for probabilistic forecasting could be explored.

This Figure shows that compression is reported both in cases where there is no ice movement in the model and in cases where there is movement. Likewise, compression is reported both in cases where the modelled maximum stress is high and low. Identifying compression cases from model data is not straight-forward.

At the beginning of the project, we enabled ice compression variables in FMI's NEMO forecasting suite on an experimental basis (M1). The results were only available internally for development purposes. At the time of writing this report, these continue to be produced on a regular basis.

Updating operationally used ice model products at FMI

To ensure the reliability of operational forecasting, it is important that sufficient testing of model products can be completed before full operationalization. New operational products need to meet all the standards set for operational forecasts.

Before new or updated model-based forecast products reach users at FMI, several different steps need to be taken. The first step is to create and test a configuration of the numerical model. After a model configuration is tested and set for operationalization, the next step is to implement the model configuration within the production system at FMI. The third step is then to define and update the forecast products that are visible for users. This third step is simple for the case where an existing product is being updated but is substantially more involved when new products are designed.

The first step on this path to operationalization was completed at M6 when the validation of the configuration of the new system was completed. This newly developed version of the national NEMO based oceanographic forecasting system was originally aimed to be fully implemented to the FMI forecasting system at M9 (which translated to early 2025 after project extension). However, due to unforeseen technical challenges not related to this project, the implementation of the new configuration to the production system (the second step towards full operationalization) was delayed until at least May 2025. The main issue we faced was the availability of key personnel resources required to update the production environment. This meant that the updated products were not available to the end users at the end of the project, as had originally been planned.

Accordingly, the system was not ready as planned for the extended ice compression forecast testing in winter-spring 2025. Furthermore, the ice winter of 2024-2025 was mild and thus not optimal for testing the new system. Together, these factors meant that this test was not concluded as planned before the extended running time of the project ran out at the end of April 2025. This test is now planned for the winter of 2025-2026, provided sufficient resources can be secured for the test. The full operationalization of the new model system, including compression forecasts (the third step), will hopefully happen in 2026.

Future Work

During the implementation phase, we identified the following areas where further work is needed.

1. **Data assimilation.** We envision improvements to the data assimilation system at FMI, so that it will eventually include data assimilation for sea ice. This would enable the model state to remain closer to reality, which makes it easier to interpret the produced forecast. However, the lack of such a data assimilation system at present does not necessarily prevent the system from being used in forecasting, as an experienced forecaster is able to take any deviation in the model initial state into account while preparing the final forecast product.

2. **Brash ice.** Currently, the ice forecasting system does not consider brash ice. However, this was identified as a possible future product by the users of the forecasts. Creating such a product would require additional research.

3. **Operational metrics.** Measuring the success of forecasts can be challenging, in particular for sea ice forecasts. Simple, routinely employed metrics, such as sea ice extent, are useful for development but are not well-suited to the actual work that duty forecasters do. Additional research into more relevant metrics might be worthwhile.

4. **Ensemble forecasts.** The possibility of providing ice ensemble forecasts from the new system should be explored. Finding cost-effective ways of doing this would make other developments such as compression forecasting more easily feasible.

5. **Further fast ice improvements.** Reading a fast ice mask into the model from ice charts might be a sensible approach. This feature already exists in upstream NEMO versions not yet in operational or pre-operational use and should be tested once those versions are ready for pre-operational tests.

Conclusions

During this project, we implemented several stakeholder relevant changes to the sea ice forecasting system at the Finnish Meteorological Institute.

The most important change was the update of the operational NEMO ocean-sea ice modelling system at FMI. During this work it was possible to update the core forecasting model and lessen the burden of technological debt in the system significantly. This work will be visible to end users as more reliable availability of sea ice forecasts.

Second, we made progress towards the implementation of operational compression forecasts at FMI. However, development steps remain to be completed. Full operationalization of compression forecasts is planned for 2026 at the earliest, after further development and sufficient operational testing has been concluded.

Further improvement needs were identified during the project and are detailed in this report. Additional project funding will be sought to continue this work. Provided that such funding can be secured, that development work will directly benefit from the work already done in this project.

This project made it possible to do much of the work required to bring NEMO-based sea ice forecasting into operational practice at FMI. Currently, the legacy HELMI-based system is expected to be retired in the medium term. If this plan is realized, the results of this project will already soon be directly benefitting both internal and external users of FMI's sea ice forecasts.

References

Eriksson P., Haapala J., Heiler I., Leisti H., Riska K. and Vainio J., 2009: Ships in Compressive Ice, Winter Navigation Research Board, Research Report No. 59, 42 p. https://www.traficom.fi/sites/default/files/10737-Report_No_59_Ships_in_Compressive_Ice.pdf

Eriksson, Patrick B., Lensu, Mikko, Haapala, Jari, and Jonni Lehtiranta. 2015. Improving Ice Pressure Forecasting for Operational Purposes. OTC Arctic Technology Conference, Copenhagen, Denmark. doi: https://doi.org/10.4043/25595-MS

Haapala, J., Lönnroth, N. and Stössel, A. 2005. A numerical study of open water formation in sea ice, J. Geophys. Res., 110. C09011. https://doi.org/10.1029/2003JC002200

Hordoir, R., Axell, L., Höglund, A., Dieterich, C., Fransner, F., Gröger, M., Liu, Y., Pemberton, P., Schimanke, S., Andersson, H., Ljungemyr, P., Nygren, P., Falahat, S., Nord, A., Jönsson, A., Lake, I., Döös, K., Hieronymus, M., Dietze, H., Löptien, U., Kuznetsov, I., Westerlund, A., Tuomi, L., and Haapala, J. 2019. Nemo-Nordic 1.0: a NEMO-based ocean model for the Baltic and North seas – research and operational applications, Geosci. Model Dev., 12, 363–386, https://doi.org/10.5194/gmd-12-363-2019

Kärnä, T., Ljungemyr, P., Falahat, S., Ringgaard, I., Axell, L., Korabel, V., Murawski, J., Maljutenko, I., Lindenthal, A., Jandt-Scheelke, S., Verjovkina, S., Lorkowski, I., Lagemaa, P., She, J., Tuomi, L., Nord, A., and Huess, V. 2021. Nemo-Nordic 2.0: operational marine forecast model for the Baltic Sea, Geosci. Model Dev., 14, 5731–5749, https://doi.org/10.5194/gmd-14-5731-2021

Lensu M., Haapala J., Lehtiranta J., Eriksson P., Kujala P., Suominen M., Mård A., Vedenpää L., Kõuts T., Lilover M.-J. 2013. Forecasting of Compressive Ice Conditions, the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, June 9-13, 2013, Espoo, Finland.

Madec, G. and the NEMO System Team. 2023. NEMO Ocean Engine Reference Manual, Zenodo, https://doi.org/10.5281/zenodo.8167700

SMHI (Swedish Meteorological and Hydrological Institute), DMI (Danish Meteorological Institute), FMI) Finnish Meteorological Institute, BSH (Federal Maritime and Hydrographic Agency), TalTech (Tallinn University of Technology). 2024. NEMO BAL MFC EIS-202411. Zenodo. https://doi.org/10.5281/zenodo.14507734

Vancoppenolle, M. 2023. SI3, the NEMO Sea Ice Engine. Zenodo. doi: 10.5281/zenodo.7534900.