

We would like to thank the reviewer for the constructive comments. Please find below our responses to the comments.

1 Content

The authors Palerme, Lavergne, Rusin, Melsom, Brajard, Kvanum, Sørensen, Bertino and Müller present a study on sea-ice concentration forecasts with lead times up to 10 days. They develop post-processing methods based on supervised machine learning and show that these outperform both TOPAZ4 and persistence sea-ice concentration forecasts. Also, they evaluate the impact of different types of predictors.

2 General comments

I thank the authors for submitting this already very mature manuscript, which I enjoyed reading and mostly had no problems comprehending. I got a bit lost when it came to the details of the model architecture, but that may be clearer to someone with a stronger AI background. If your target group is people with little AI background, I would suggest boiling down the technical description and spending a bit more time on explaining the terms (see detailed comments below). One aspect where I see room for improvement is the clarity of the motivation. Support of maritime operations is mentioned very prominently in both Abstract and Introduction. Yet, I find little information on crucial aspects for this like timeliness of the forecasts, infrastructure for providing the forecasts to ships operationally or the spatial resolution of the model outcome, compared to what is needed for navigational needs. So, I was wondering whether the current study is intended to be a proof of concept, with the applicability being the focus of future work. It would be good if the authors could clarify this, and elaborate upon for which other aspects their study is relevant besides supporting of maritime operations. In summary, I suggest to accept this paper for publication after minor revisions.

3 Specific comments

Abstract

General impression: A very concise and yet comprehensive description of your paper. I find little to criticise. **L1:** If operational support is your main motivation, I would suggest to add some brief information on the timeliness of your forecasts to the Abstract, as this is crucial for operational use. By how much does the post-processing delay the availability of forecasts, and does the accuracy increase achieved by post-processing outweigh this?

We agree with this comment, and we have added the following sentence in the abstract:

Predicting the sea ice concentration for the next 10 days takes about 4 minutes (including data preparation), which is reasonable in an operational context.

Introduction

General impression: A very good description of the existing literature on sea-ice forecasting. You could be a bit clearer on what the new aspects are that your study adds to the body of literature. I would also like to see a bit more details on the motivation and relevance of your study. It is certainly relevant, but it could be made clearer for what. Also, you could end the Introduction by formulating your research goals/questions, which can then be picked up in the Discussion and conclusion section.

L16: . . . is often limited by their inaccuracies: I agree, but a reference would be good Nevertheless.

We have added the following reference:

Veland, S., Wagner, P., Bailey, D., Everet, A., Goldstein, M., Hermann, R., Hjort-Larsen, T., Hovelsrud, G., Hughes, N., Kjøl, A., Li, X., Lynch, A., Müller, M., Olsen, J., Palerme, C., Pedersen, J., Rinaldo, Ø., Stephenson, S., and Storelvmo, T.: Knowledge needs in sea ice forecasting for navigation in Svalbard and the High Arctic, Svalbard Strategic Grant, Svalbard Science Forum. NF-rapport 4/2021, 2021

L17-19: If mentioned in Melsom et al. (2019), consider giving the accuracy for summer instead of a yearly mean, since that is when most of the maritime traffic happens. Large seasonal variability should still be mentioned.

In Melsom et al. (2019), there is no mean value reported for the summer period, though it can be seen that the errors are larger during the summer in figure 6 from Melsom et al. (2019). We have decided to modify the following sentence:

Melsom et al. (2019) reported that the location of the ice edge is predicted with a mean accuracy of 39 km in 5-day forecasts from the TOPAZ4 prediction system (Sakov et al., 2012), with large seasonal variability in the forecast performances.

by:

Melsom et al. (2019) reported that the location of the ice edge is predicted with a mean accuracy of 39 km in 5-day forecasts from the TOPAZ4 prediction system (Sakov et al., 2012), with larger errors during the summer when most of the maritime traffic occurs (Müller et al., 2023).

L22: I find it a bit counter-intuitive to mention seasonal time scales when speaking about weather forecasts, which for me would be up to ten days. I would suggest to either simply speak about forecasts without specification on weather forecasts, or to refer only to those studies which focus on up to ten days lead time.

The following statement:

Statistical correction techniques (often called calibration) have been applied to weather forecasts at time scales ranging from hours to seasons

has been replaced by:

Statistical correction techniques have been applied to atmospheric forecasts at time scales ranging from hours to seasons

Last paragraph: You could be clearer on what precisely the goal of your study is. Which is the gap that you want to fill? Starting the paragraph with a sentence on what the new thing on your study is, and then elaborating on the why, would be a good transition towards the rest of the paper.

We think that we have already justified this in the beginning of the paragraph, but we have slightly modified this paragraph. Please find below the paragraph in the revised version of the paper:

Most of the short-term sea ice prediction systems based on machine learning do not use predictors from dynamical sea-ice models (Fritzner et al., 2020; Liu et al., 2021; Grigoryev et al., 2022; Ren et al., 2022; Keller et al., 2023), and it is currently unclear whether adding such predictors would significantly improve forecast accuracy. This study aims at assessing the impact of using predictors from dynamical sea ice models in the development of SIC forecasts from machine learning, as well as the impact of post-processing SIC forecasts from a dynamical sea ice model for lead times from 1 to 10 days.

Data

General impression: Good to understand. Partly contained elements which I would suggest shifting to the Results or Methods section (see comments below).

L78: Good to see that you did this analysis, but I would move it to the Results section and focus on the data description here.

We agree with the reviewer, and we moved the paragraph which was previously between the lines 71 and 84 to the Results section in a new subsection called “3.1 Sea ice concentration observations”.

L95: Would be interesting to see later on if that impacts the forecast performance.

We agree that it would be interesting to evaluate the impact of model developments over time. However, though re-forecasts are currently produced at 9 km resolution from ECMWF IFS, they are only produced on Mondays and Thursdays of the current year and on the corresponding date for the previous 10 years. Therefore, if a reforecast dataset is produced on Thursday 25-01-2024, the reforecast dataset will be produced for every 25-01 of the previous 10 years. While only TOPAZ4 forecasts produced on Thursdays are stored in the long term archive, there are no ECMWF reforecasts available for most Thursdays of the preceding 10 years. This makes it difficult to assess the impact of using the operational ECMWF weather forecasts.

L97–116: Contains many elements where you describe what you do with the data, rather than which data you use. Consider shifting these elements to the Methods section, or merging Data and Methods section.

We agree with this comment. Therefore, we merged the Data and Methods sections together.

L97–105: I think it would help to add the categories in the table, and sort the table after categories, in the same order as they appear in the text.

We have presented the predictors in the text in the same order and the same categories as in table 1. Please find below the new paragraph:

In this work, the deep learning models have been developed using 8 predictors that can be divided into three categories (table 1). First, two predictors are derived from AMSR2 SIC observations acquired before the forecast start date, and consist of the SIC observations from the day preceding the forecast start date, and the SIC trend calculated over the 5 days preceding the forecast start date (in % per day). The second category consists of weather forecasts from ECMWF that have been averaged between the forecast start date and the predicted lead time. These predictors are the 2-m temperature, as well as the x and y components of the 10-m wind on the grid used for the deep learning models. Then, predictors from the TOPAZ4 ocean model can be considered as the last category. These variables are the SIC forecasts for the predicted lead time, the difference between TOPAZ4 SIC during the first daily time step and the SIC observed the day before (hereafter referred to as "TOPAZ4 initial errors"), and the land sea mask (constant predictor).

L113: Does this influence the training, in the sense that the model is trained for points which are discarded later anyway, potentially diminishing the forecast quality for other, "real" points?

We have tested three different approaches for dealing with land grid points. The first approach consists of considering land grid points as ice-free ocean (the one used in the paper). The second approach consists of interpolating the nearest ocean grid point over land (this approach was used by Wang et al., 2017 and Kvanum et al., 2024). The last approach consists of using partial convolution, which is a method where the land grid points are masked during the convolution operations, and which was used by Durand et al., 2023. We have compared these three approaches in the figure below, and we decided to consider land grid points as ice-free ocean based on this comparison. We have added this figure in the supplement. Furthermore, the use of a land-sea mask in the predictors probably provides enough information for predicting the land grid points correctly.

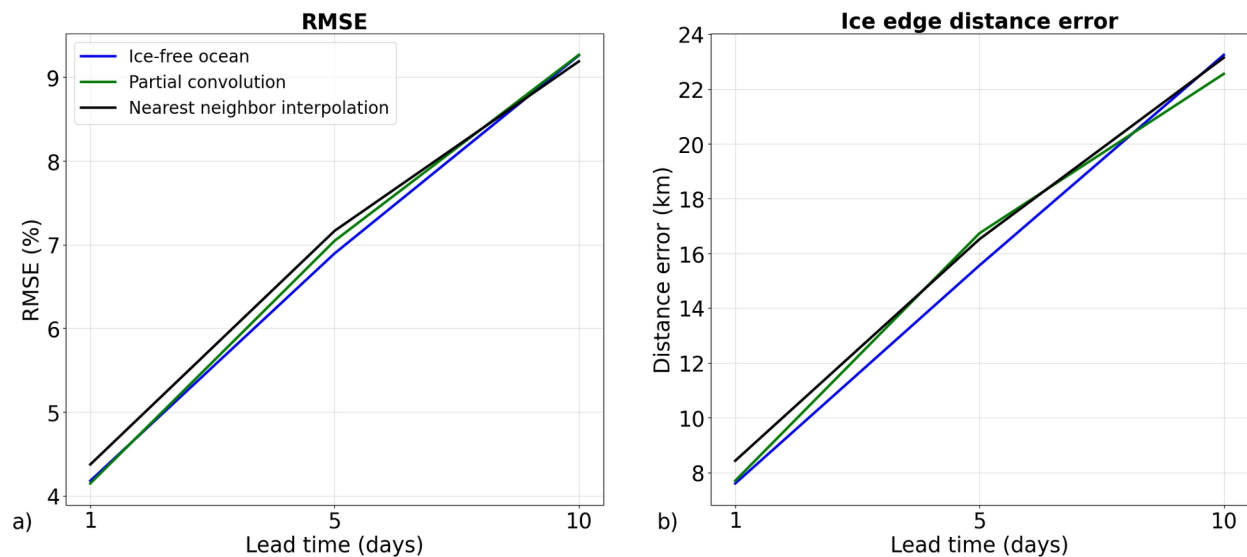


Figure S2. Performances of the deep learning models with the Attention Residual U-Net architecture during 2021 (validation period) with three different approaches for filling land grid points. Blue curves: land grid points are considered as ice-free ocean. Black curves: the land grid points are filled using the value of the nearest ocean grid point. Green curves: partial convolution is used, which is a method where land grid points are masked. AMSR2 sea ice concentration observations are used as reference.

Durand, C., Finn, T. S., Farchi, A., Bocquet, M., and Òlason, E.: Data-driven surrogate modeling of high-resolution sea-ice thickness in the Arctic, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2023-1384>, 2023.

Kvanum, A.F., Palerme, C., Müller, M., Rabault, J., Hughes, N. (2024). Developing a deep learning forecasting system for short-term and high-resolution prediction of sea ice concentration, EGU sphere [preprint],

Wang, L., Scott, K., and Clausi, D.: Sea Ice Concentration Estimation during Freeze-Up from SAR Imagery Using a Convolutional Neural Network, Remote Sensing, 9, 408, <https://doi.org/10.3390/rs9050408>, 2017.

Methods

General impression: Section 3.1 was quite hard to comprehend due to the use of many technical terms, which I myself am not very familiar with. May be different for people with a strong AI background. Sections 3.2 and 3.3 were much clearer to me and do not need improvement, except for one question which I raise below.

L124–143: I find the description quite technical. Explaining, or, if they are not crucially needed, omitting terms like "residual connections", "convolutional/attention blocks" or "average pooling" would help to understand non-AI experts to follow your methodology.

We agree that the description is technical and can be difficult to understand for people who do not have a machine learning background. However, we think that this section is necessary in order to make the work reproducible and we also introduced some novel approaches for sea ice forecasting using deep learning here. Furthermore, we also think that this is not the role of such a paper to explain all the machine learning terms because this would be very long. We rather think that people without a machine learning background interested in understanding the method in depth can read the papers cited in our paper, or / and look at some online tutorials explaining these concepts. It is also worth noting that the rest of the paper can be understood without understanding all the details of the deep learning that we developed. Nevertheless, we have modified this section in order to make it a bit more understandable. Therefore, the following sentences:

First, some models were developed using residual connections (He et al., 2016) in the convolutional blocks, meaning that the residual was learned at each block. This has been shown to ease neural network training (He et al., 2016). Furthermore, the impact of using attention blocks introduced by Oktay et al. (2018) in the decoder, and designed to improve predictions in challenging areas, is also evaluated. The benefit of using attention blocks for sea ice forecasting was already shown by Ren et al. (2022) who developed an attention block (different from the one used in this study) for sea ice prediction with a fully convolutional network. Finally, average pooling was used in the downsampling blocks of the encoder instead of max pooling due to slightly better performances observed during the tuning phase (see supplement).

have been replaced by:

First, some models were developed using residual connections (He et al., 2016) in the convolutional blocks (meaning that the residual was learned at each block), which was shown to ease neural network training (He et al., 2016). It is worth noting that the residual U-Net architecture was used by Keller et al. (2023) for predicting the sea ice extent in the Beaufort

sea. Furthermore, the impact of using attention blocks introduced by Oktay et al. (2018) in the decoder, and designed to give more weight (attention) on areas that are challenging to predict (these regions are identified by the attention blocks during training), is also evaluated. The benefit of using attention blocks for sea ice forecasting was already shown by Ren et al. (2022) who developed an attention block (different from the one used in this study) for sea ice prediction with a fully convolutional network. Finally, average pooling was used in the downsampling blocks of the encoder instead of max pooling due to slightly better performances observed during the tuning phase (see supplement).

L146: Does this also contain the "fake ocean points" described in L113, and if yes, does that influence the results?

The land grid points were filled with valid values for oceanic variables. In line 113, we wrote: *When providing the predictors to the neural networks, all the grid points must contain valid values, meaning that the land grid points must be filled with valid values for oceanic variables.*

In the manuscript, we wrote the following sentence:

In order to analyze the full range of SIC values in the forecasts, as well as to strongly penalize large errors, the root mean square error (RMSE) is calculated over all oceanic grid points.

Because the RMSE is calculated over all oceanic grid points, the land grid points which were filled with valid values were not taken into account for evaluating the deep learning models.

L167: TOPAZ should be TOPAZ4 (also in other places, occurred several times).

Thanks for noticing this. We have used TOPAZ4 everywhere in the revised version of the manuscript.

Results

General impression: As for the other sections, I find little to criticise. I did have some open questions, but nothing major.

L175: Does the varying number of model parameters influence the results, in the sense that you get more precise results for the Attention Residual U-Net models simply because there is a larger number of model parameters to optimize upon?

This is a good point. Yes, the number of parameters influences the performances. However, it is difficult to quantify the impact of the number of parameters without changing the architecture. Nevertheless, residual connections are known to speed up model training (less epochs are necessary to achieve similar performances) and attention blocks are designed to improve the

performances in challenging areas (more weight is given to these areas). Therefore, though the impact of the number of parameters is difficult to assess, we believe that residual connections and attention blocks also significantly impact the performances. Furthermore, in figure 3, while the original U-Net architecture is the model containing the lowest number of parameters (31 millions), it performs better than the Attention U-Net (37 millions parameters) for most lead times. This tends to show that the residual and attention blocks have a larger impact on the predictions than the number of parameters.

The following statement:

It is worth noting that the architecture influences the number of model parameters

has been replaced by

It is worth noting that the architecture influences the number of model parameters, which can also influence the performances

L184: Did you also see the spurious SIC which the Attention U-Net shows on other dates? Generally, concerning Fig. 2: It is fine to show only one day's maps as example, but it would be good to know if you also looked at other dates and how representative this date is for the overall development, how the RMSE's etc evolve over time. Since the ice refreezes rapidly at this time and the SIC is likely varying less in mid-winter, it would be interesting to see if you can also see that in the temporal development of the RMSE's and the comparison to your benchmarks.

Thanks for this comment. We have replaced the following sentences:

The model with the Attention U-Net architecture produces very small positive SIC (lower than 2 %) in large areas where no sea ice is observed during the target date. Nevertheless, it seems that adding residual blocks to this model (resulting in the Attention Residual U-Net architecture) helps to better predict these areas.

by:

The model with the Attention U-Net architecture produces very small positive SIC (often lower than 2 %) in large areas where no sea ice is observed during the target date, which is a pattern often observed with this model for other dates as well. Nevertheless, it seems that adding residual blocks to this model (resulting in the Attention Residual U-Net architecture) consistently helps to better predict these areas.

Furthermore, we consider that the evolution of the RMSE over time is shown in figure 8 of the preprint.

L200–206: Do you know why the TOPAZ4 RMSE is higher than the persistence benchmarks for all lead times? Wouldn't you expect it to be better? It's not the focus of your paper, so don't spend too much room on this, but it was one of the first things which came to my mind when looking at Fig. 4.

This is an interesting question, but we do not know why TOPAZ4 performs worse than persistence. We consider that analyzing the reason why TOPAZ4 produces such results is beyond the scope of our paper. Nevertheless, one reason might be that the AMSR2 sea ice concentration product used in our study might significantly differ from the passive microwave observations assimilated in TOPAZ4.

L206ff: It would be interesting to see how removing predictors influences the runtime of the model. You could discuss, for example, whether the advantage gained in runtime outweighs the small benefit of including TOPAZ4 predictors, and if this might be reason enough to drop the TOPAZ4 predictors altogether.

We added the following sentences in the section "Discussion and conclusion":

While it takes less than a second to predict the sea ice concentration for one lead time on a 12 GB GPU (NVIDIA Tesla P100 PCIe) once the list of predictors is available, the full processing chain including the production of the predictors on a common grid takes about 4 minutes for all lead times. This is negligible compared to the time necessary for producing TOPAZ4 forecasts, and therefore reasonable in an operational context.

Since it takes less than a second to produce the forecasts for one lead time and only 4 minutes for the full processing chain, we consider that the advantage of dropping TOPAZ4 forecasts is very small for the run time of the deep learning model.

Figure 5: It would be good if the colors of the bars would be consistent with those in Figure 4.

We made the figures 4, 5, and 8 using consistent colors.

Discussion and conclusion

The section provides a good summary of your findings, and puts them nicely into perspective with other studies. You could state your conclusions more clearly. This could for example be done by formulating a clear goal or research question(s) at the end of the Introduction which you can pick up and answer here to provide a nice framework for your paper.

We expressed the question of quantifying the impact of predictors from a dynamical sea ice model on the predictions from the deep learning models in the introduction:

Most of the short-term sea ice prediction systems based on machine learning do not use predictors from dynamical sea-ice models (Fritzner et al., 2020; Liu et al., 2021; Grigoryev et al., 2022; Ren et al., 2022; Keller et al., 2023), and it is currently unclear whether adding such predictors would significantly improve forecast accuracy. This study aims at assessing the impact of using predictors from dynamical sea ice models in the development of SIC forecasts from machine learning, as well as the impact of post-processing SIC forecasts from a dynamical sea ice model for lead times from 1 to 10 days.

And we answered this question in the section Discussion and conclusion:

The impact of using predictors from TOPAZ4 sea ice forecasts is much lower since these predictors lead to a reduction in RMSE of only 2.1 % on average. While the impact of using sea ice forecasts from TOPAZ4 is limited in this study, this does not mean that using predictors from sea ice forecasts does not have stronger potential. TOPAZ4 is an operational system that has been constantly developed since 2012, which can lead to inconsistencies limiting the impact of these predictors. The production of consistent re-forecasts with operational systems could increase the impact of sea ice forecasts in the development of such methods, and should be recommended in the sea ice community. Furthermore, it is likely that more accurate physical-based sea ice forecasts would have larger potential as predictors for machine learning models.

Also, I am missing a discussion on the practical applicability of your study. In the Abstract and Introduction, you name increasing marine traffic as one reason why short-term sea-ice forecasting is relevant. It would be interesting to discuss in how far your model is ready to support decision making for marine operations: How fast would your products be available? Do you have the means to transfer them in near-real time? Does the precision of your results meet the requirements of the onboard ship personnel? Or is your paper rather a proof of concept that it is possible to achieve high-quality short-term forecasts using deep learning, and the transfer to near-real time applications is something which could be done in future?

We agree that this point was not very clear in the preprint. Therefore, we have added the following sentences:

While it takes less than a second to predict the sea ice concentration for one lead time on a 12 GB GPU (NVIDIA Tesla P100 PCIe) once the list of predictors is available, the full processing chain including the production of the predictors on a common grid takes about 4 minutes for all lead times. This is negligible compared to the time necessary for producing TOPAZ4 forecasts, and therefore reasonable in an operational context. However, the production of TOPAZ4 forecasts will be stopped in February 2024, and the AMSR2 SIC observations used in this study are not available in near real time yet. This prevents the operational use of the post-processing method presented here.

And the following sentences:

While this study focused on developing pan-Arctic SIC forecasts at the same resolution as the TOPAZ4 prediction system (12.5 km), there is also a need for higher resolution (kilometer scale) sea ice forecasts (Wagner et al., 2020). This can be addressed by developing regional high resolution prediction systems using deep learning such as the recent works from Keller et al. (2023) and Kvanum et al., (2024).