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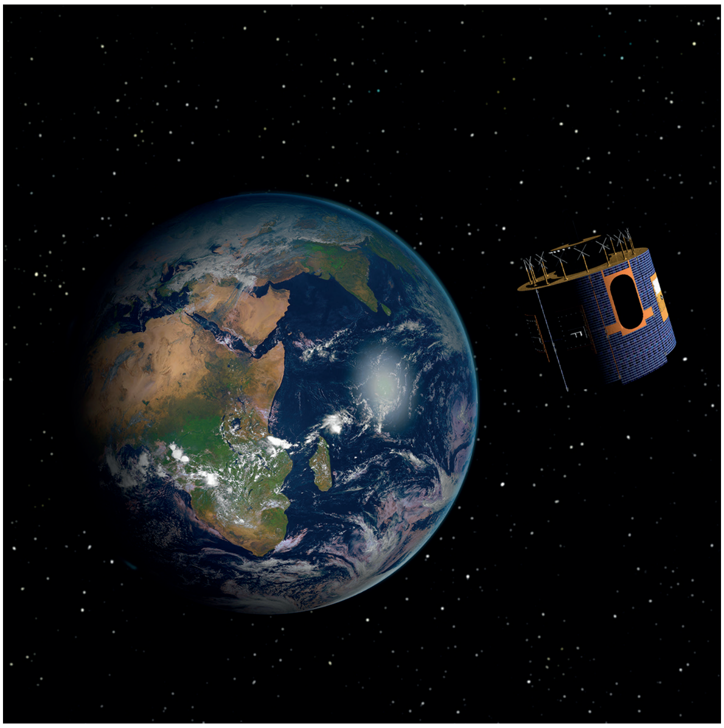

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Dynamic sea ice in the IFS

Sarah Keeley, Kristian Mogensen

Including more Earth system components in numerical weather prediction models has the potential to improve weather forecasts because of the interactions of those components with the atmosphere and with each other. One such component is sea ice. Until a few years ago, it was assumed that sea ice fields change so slowly that it is acceptable to keep them fixed for the period covered by global medium-range forecasts. Although this may be true for the total pack ice, in regions close to the ice edge, where there is often rapid growth or melt, this assumption is not justified. The presence of sea ice influences surface fluxes, especially when the overlying atmosphere is much colder than the ocean, as is usually the case in winter. Fluxes can be several hundred W/m^2 over open water and zero over thick ice. Open water thus provides a local heat source which has the potential to alter the local and also the wider meteorological situation.

In November 2016, ECMWF included a dynamic–thermodynamic sea ice model in ensemble forecasts (ENS) as part of an upgrade of its Integrated Forecasting System (IFS Cycle 43r1). Since the implementation of IFS Cycle 45r1 in June 2018, high-resolution forecasts (HRES) have also benefitted from dynamic coupling between sea ice, the ocean and the atmosphere.

Here we show why the assumption of persistence of sea ice concentration is not suitable for medium-range forecasts; we describe the sea ice model used at ECMWF; and we present some regional case studies that illustrate how the model is able to capture relatively rapid changes in sea ice concentration. Verification results show that using the dynamic sea ice model generally improves sea ice predictions, which in turn has repercussions on local 2-metre temperature forecasts. The impact on large-scale atmospheric forecast performance is mostly neutral.

Limitations of persistence

To illustrate the need for modelling sea ice dynamically rather than using a simple model of persistence, we consider the sea ice conditions for the year April 2017 to March 2018. To assess how persistent the ice field was, we calculated the difference between the sea ice analysis field from OCEAN5 on any given day and the same field on each of the following ten days (see Box A for details on OCEAN5). For each of the following ten days, if the change in sea ice concentration at a model grid point was more than 15%, we considered that a significant change had occurred. We then calculated the total area in which a change in sea ice concentration of more than 15% occurred, as a proportion of the total sea ice field. We chose to use OCEAN5 rather than OSTIA as it is less susceptible to fluctuations due to erroneous data, which can appear from time to time in the OSTIA product (see Box A for more details on OSTIA).

A

OSTIA and OCEAN5

OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) (*Donlon*, 2012) is a daily sea-surface temperature (SST) and sea ice analysis product produced by the UK Met Office. The SST analyses are made using observations from satellite and in situ platforms. The sea ice field is a regridded version of the OSI-SAF sea ice product derived from passive microwave observations. It is not necessarily consistent with the SST at the same grid point and uses a relatively simple interpolation method to infill missing data to produce a globally complete gridded sea ice field. This means that the system is very sensitive to missing data. If large areas are missing from a day’s analysis, the OSTIA system cannot provide values. Close to the coast, where the OSI-SAF microwave product is unable to distinguish between land and ice and returns missing data values, the OSTIA product interpolates to the land–sea mask. This can lead to unphysical sea ice concentrations in regions marked by complex coastlines, e.g. in the Gulf of Finland.

OCEAN5 is ECMWF’s ocean and sea ice reanalysis and real-time analysis system. It estimates the state of the sea ice and 3D ocean by using a 3D variational assimilation system (NEMOVAR). The system produces initial conditions for the sea ice model by assimilating daily sea ice concentration values which come from the gridded sea ice concentration of OSTIA. By assimilating the sea ice concentration OSTIA data, there is better physical agreement between the SST and sea ice field and the system is less susceptible to missing data as there is memory in the assimilation system.

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Figure 1 shows the monthly mean percentage area in which significant changes occurred over periods of time ranging from one day to ten days. The first thing to note is that there are times of the year when the ice concentration is particularly active. In both hemispheres, the greatest activity is in the early autumn as the hemisphere transitions into the polar night. In those conditions sea ice can form rapidly. As shown in Figure 1, the assumption that the ice concentration remains static is a poor assumption at this time of year even for three-day periods, with significant changes in sea ice concentration in nearly 10% of the total ice field area in the southern hemisphere. The second peak in activity occurs in the summer months when the ice is melting. It is thinner at this time, so it can rapidly be removed through local heating, and wave breaking can also play a role (*Zhang*, 2012).

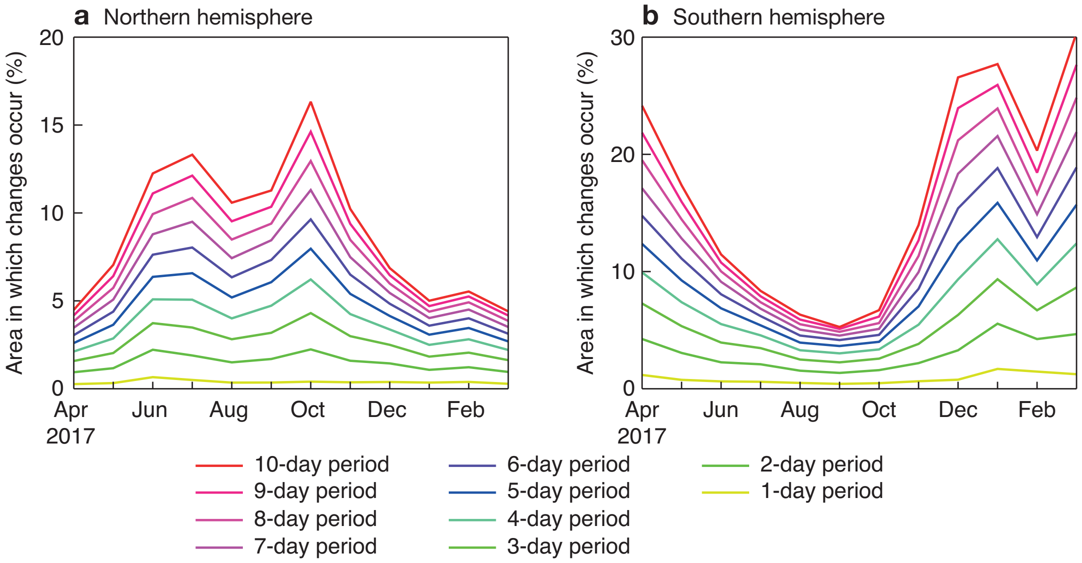

Figure 1 Monthly mean percentage of the sea ice field in which significant changes in sea ice concentration (> 15%) occur over different periods of time, based on OCEAN5 analysis fields for April 2017 to March 2018, for (a) the northern hemisphere and (b) the southern hemisphere.

Sea ice modelling and coupling

The model used to represent the sea ice dynamic and thermodynamic evolution is LIM2, which has been developed at the Belgian Université catholique de Louvain (*Fichefet*, 1997) and is part of the community ocean model NEMO (version 3.4.1). The sea ice model is relatively simple in that it has a single thickness category, and it does not model some key surface processes, such as the forming of melt ponds. However, it is computationally relatively cheap and, as we will show later, performs well at medium to sub-seasonal timescales. The sea ice model uses a rheological model to describe the internal ice dynamics, and a three-layer thermodynamic model, with two layers of ice and one of snow.

There are some limitations which have guided how we have coupled the sea ice model (LIM2) components to the atmospheric model. For example, as the parametrizations within the sea ice model are relatively simple, we cannot capture summer melt pond processes, making the albedo of the LIM2 model too high in summer. For this reason, we have continued to use the albedo climatology of the atmospheric model. Currently we only couple the sea ice concentration from LIM2. Work is ongoing to couple additional fields. Sea ice concentration is updated in the IFS every coupling step (currently every hour), but we continue to use the sea ice tile in the surface model of the IFS to adjust the surface energy balance on faster timescales.

New sea ice analysis

The sea ice model is initialised using the OCEAN5 analysis system, as is the ocean model. For sea ice observational input, OCEAN5 assimilates sea ice concentration from the OSTIA sea-surface temperature (SST) and sea ice analysis. Until June 2018, the HRES forecast was uncoupled and used the OSTIA sea ice product, which is not necessarily consistent with the OSTIA sea-surface temperature analysis and can be vulnerable to missing or spurious data in the sea ice field. Sea ice concentrations are especially hard to determine close to the coast due to contamination in the satellite retrieval caused by the effects

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of land. This means that determining the sea ice concentration within the Baltic region using passive microwave retrievals is incredibly challenging, and the OSTIA product does not always perform well in this region. To try to account for potentially unreliable data, the surface analysis for the uncoupled system removed ice below a 20% threshold. Figures 2a,b show the initial conditions of the sea ice field from the new coupled HRES using OCEAN5 and the uncoupled HRES using OSTIA. There are some differences between the two. OCEAN5 is able to adjust the sea ice concentration close to land, consistent with its SSTs, whereas the OSTIA product makes an extrapolation near the coast and fails to do this correctly, for example in the Gulf of Finland.

To highlight the impact of the new coupled system and the types of event it is able to reproduce, we show recent examples when the coupled and uncoupled systems were running concurrently and conclude with an example from the extended-range (monthly) forecast system.

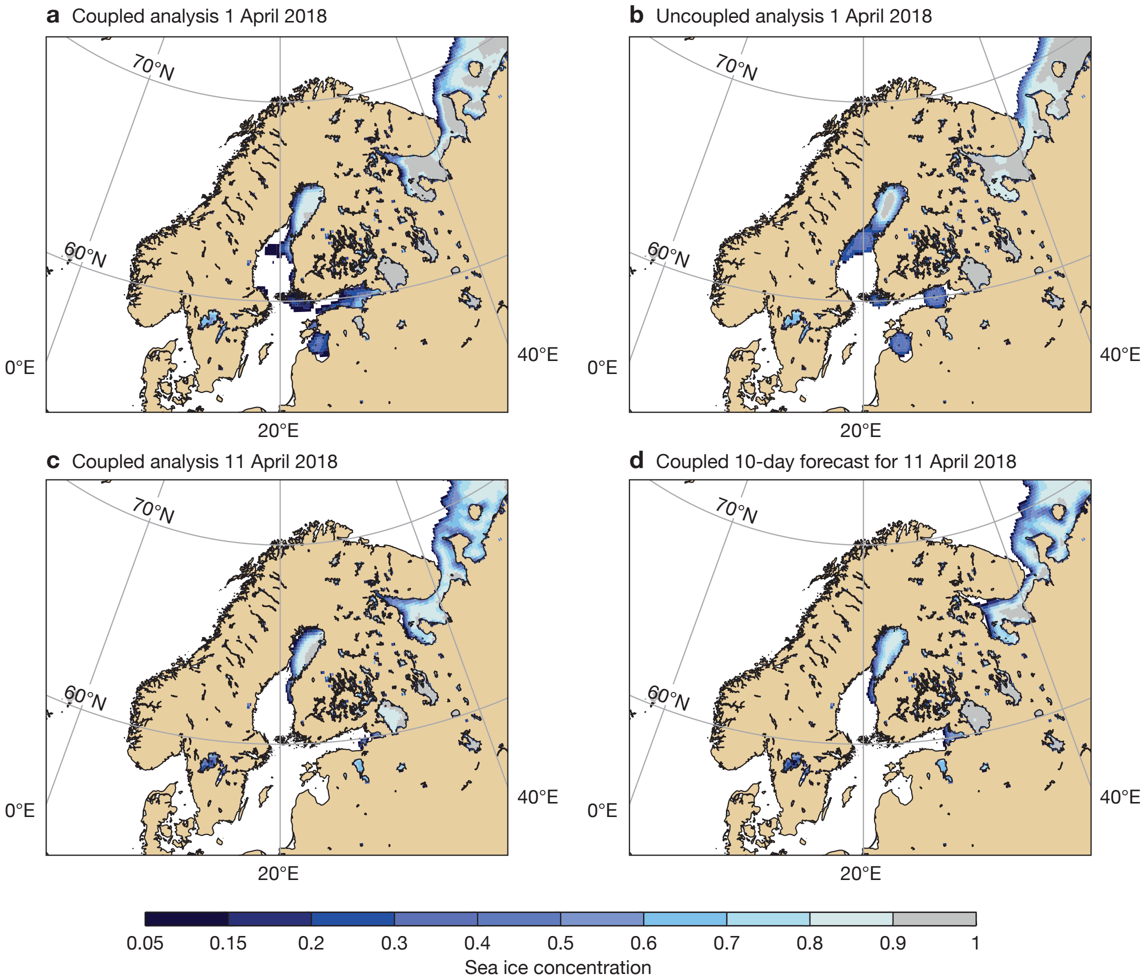

Figure 2 Performance of HRES sea ice concentration predictions with dynamic sea ice. The plots show (a) the HRES coupled analysis of sea ice concentration based on OCEAN5 for 1 April 2018, (b) the HRES uncoupled analysis of sea ice concentration based on OSTIA for 1 April 2018, (c) the HRES coupled analysis for 11 April 2018 and (d) the HRES coupled 10-day forecast for 11 April 2018.

Sea ice prediction case studies

The three case studies presented here illustrate the impact of coupling in HRES as implemented on 5 June in IFS Cycle 45r1.

Sea ice melt in the Baltic Sea

In the uncoupled configuration, the sea ice concentration is fixed for the duration of the forecast. Figure 2 illustrates the impact of having a coupled sea ice model within HRES. Figure 2c shows the state of the ice in the OCEAN5 analysis for 11 April 2018. Compared to the OCEAN5 analysis for 1 April shown in

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Figure 2a, over the course of ten days the ice has retreated within the Gulfs of Finland, Riga and Bothnia. This reduction in sea ice concentration is well captured by the coupled model, as can be seen in the 10-day forecast shown in Figure 2d.

Sea ice concentration can have a strong impact on predictions of local 2-metre temperature, although the size of the impact depends on how the surface fluxes are altered by local meteorological conditions (e.g. the overlying atmospheric temperature) and the concentration: where concentrations are high, the heat flux from the ocean to the atmosphere is significantly reduced. To illustrate this, Figure 3 shows the difference in temperature and sea ice concentration between 24-hour high-resolution forecasts with and without ocean–sea-ice–atmosphere coupling. The differences in predicted temperature in the Gulf of Bothnia of up to 6°C can largely be attributed to the differences in sea ice concentration. The size of the changes in 2-metre temperature also depends on the large-scale meteorology. For example, the temperature differences in the Gulf of Finland are not large in the forecasts shown, but they become more pronounced at longer time ranges.

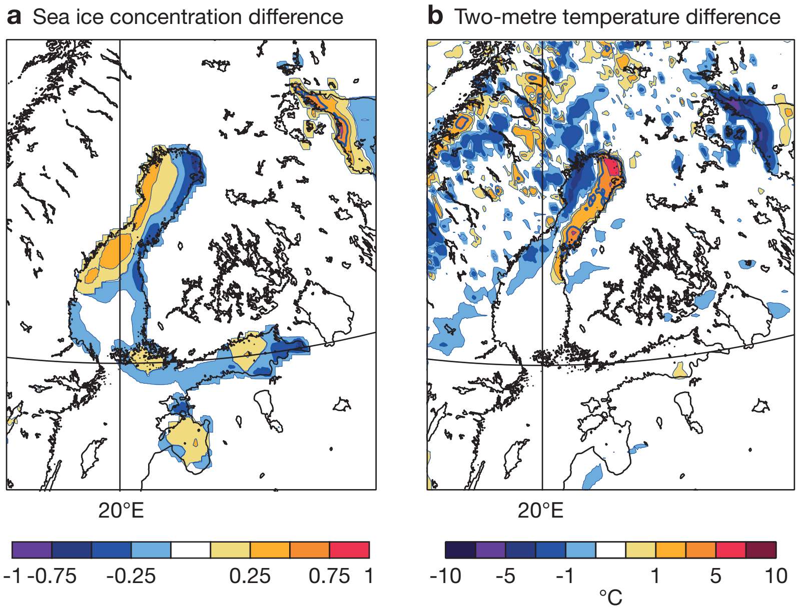

Figure 3 Difference between uncoupled and coupled 24-hour HRES forecasts for 2 April 2018 00 UTC (uncoupled minus coupled) for (a) sea ice concentration and (b) 2-metre temperature.

Opening in Greenland ice

On 24 February 2018, there was a sizeable opening in the sea ice concentration near Cape Morris Jesup in north-east Greenland (see satellite image in Figure 4d). In winter, this can be important for local temperatures as heat can be exchanged between the relatively warm underlying ocean and the cold overlying atmosphere. The opening was established over the course of a week. The event was interesting because it was mainly driven by advection of the sea ice off the coast rather than local heating. Figure 4 shows the coupled HRES forecast with different lead times initialised on 18 February, which captured the event. In addition to predicted sea ice concentration, it shows the preceding 24-hour mean 10 m wind field. Initially sea ice concentration is high even at the coast (Figure 4a), by 21 February the predicted opening has increased slightly (Figure 4b), and it continues to grow to its maximum size on 24 February after strong winds the previous day (Figure 4c).

Sea ice loss in the Bering Sea

This year the maximum sea ice extent was marked by relatively low sea ice in the Bering Sea and relatively extensive sea ice in the Sea of Okhotsk compared to recent climatology. Here we analyse the forecast taken from the monthly forecast system initialised around the day of the maximum sea ice extent for the Arctic, 12 March 2018. Figure 5a shows the control forecast analysis of the sea ice concentration for that day. Figure 5d shows the analysis on 3 May. The Bering Sea was nearly ice free by then. The sea ice extent at that time was the lowest ever recorded in the region for this time of year. In Figure 5b we show the 45-day ensemble forecast for 3 May. We see that there is a large spread in the Bering Sea, and clearly not all members are predicting that the region would have such a large loss of ice. Figure 5c shows an example of one of the ensemble members which captured the low sea ice extent in the Bering Sea by the start of May.

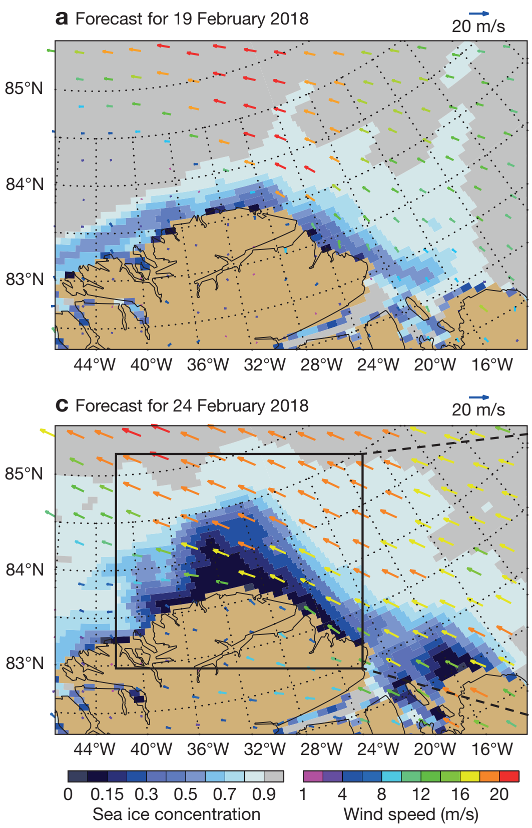

Figure 4 Evolution of sea ice concentration and the preceding 24-hour mean 10-metre wind field for forecasts initialised on 18 February 2018 and valid on (a) 19 February, (b) 21 February and (c) 24 February. Panel (d) shows the Synthetic Aperture Radar (SAR) image from the Sentinel-1B satellite for 24 February around Cape Morris Jesup. (Satellite image: European Space Agency via Danish Meteorological Institute)

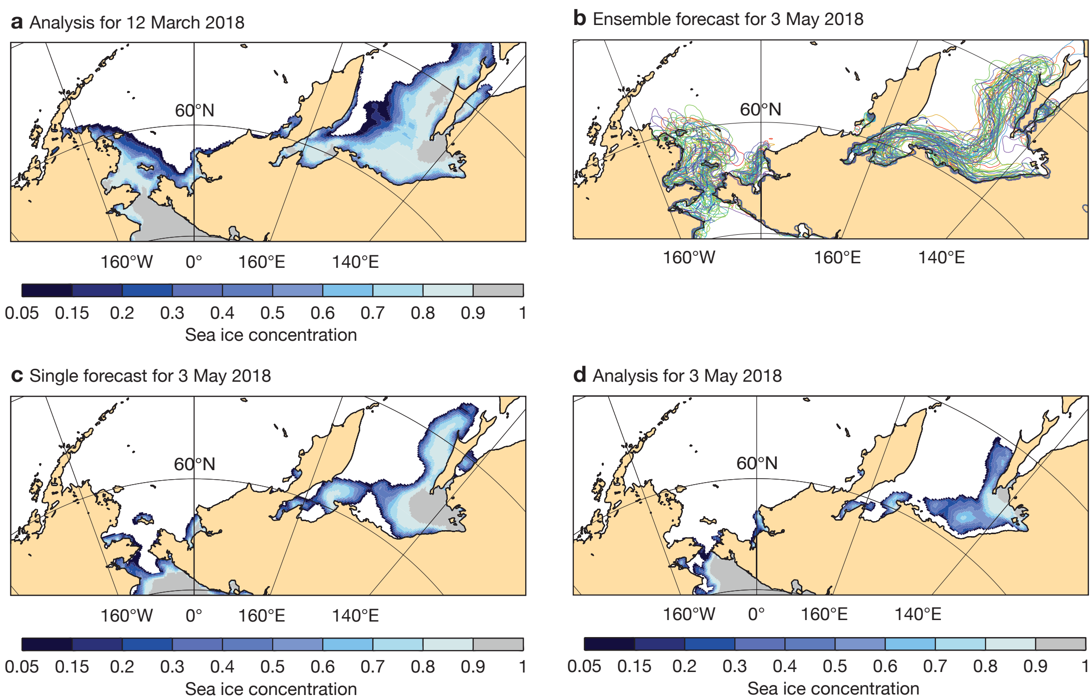

Figure 5 These maps of the Bering Sea and Sea of Okhotsk areas show (a) the analysis of sea ice concentration for 12 March 2018, (b) an ensemble spaghetti diagram for the sea ice edge from a forecast for 3 May 2018 initialised on 12 March 2018, (c) a single ensemble member prediction of sea ice concentration from the same forecast and (d) the analysis of sea ice concentration for 3 May 2018.

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Sea ice prediction performance

Differences between OSTIA and OCEAN5 analyses pose a difficulty when verifying the performance of the sea ice model. Using one or the other of the analyses will favour either the uncoupled or the coupled model. For example, low sea ice concentrations are not present in the OSTIA analysis due to the removal of low concentrations in the preprocessing of the product for use in the uncoupled HRES, whereas OCEAN5 and the coupled model contain ice concentrations from 0 to 100%. Work is ongoing to develop appropriate verification measures for sea ice. To look at broad model performance, we show comparisons between coupled and uncoupled forecasts verified against the OSTIA analysis from the uncoupled system. If anything, this penalises the coupled forecasts more. First we consider the change in bias over the course of the forecast.

Figure 6 shows the growth in sea ice concentration bias with increasing forecast lead time for the northern hemisphere for the four seasons. In all seasons, the growth in bias is slower in the coupled model than in the uncoupled model. This highlights again why persisting the ice field is not an appropriate assumption. In winter, the coupled model bias change is opposite in sign to the uncoupled model bias change, showing that the coupled model tends to form ice more rapidly than observed. The difference between the uncoupled and coupled growth in bias is greatest in summer and smallest in winter. This is consistent with the persistence measure in Figure 1.

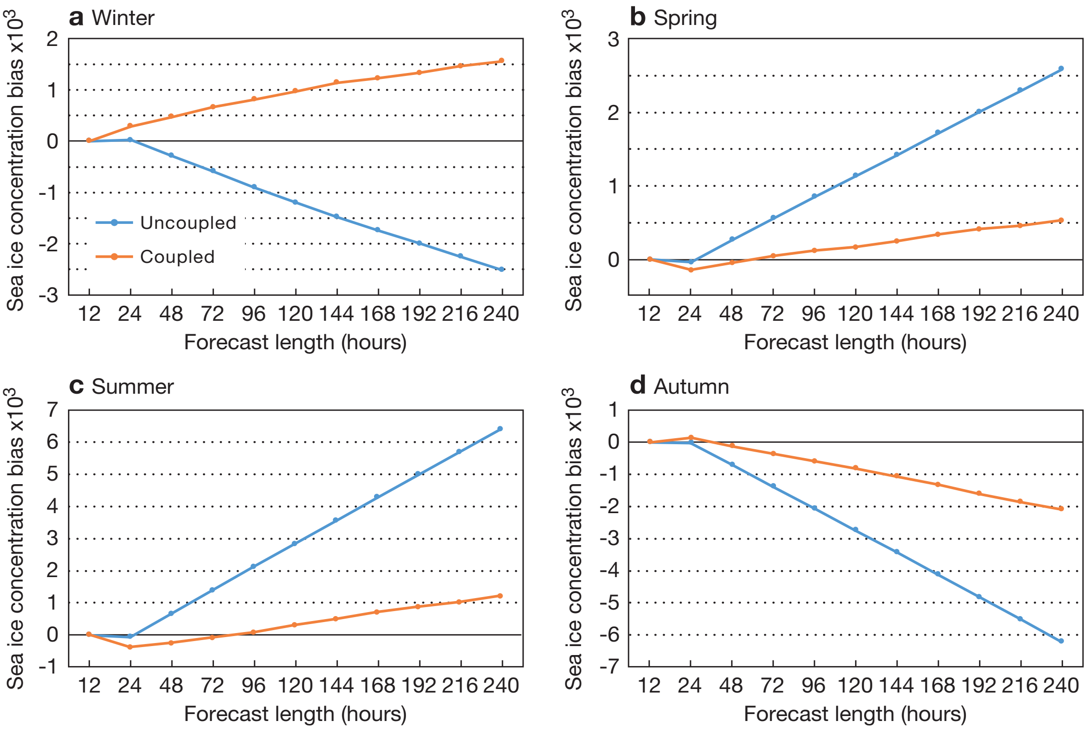

Figure 6 Sea ice concentration bias (minus initial bias) by forecast period for the northern hemisphere in (a) winter (December–January–February), (b) spring (March–April–May), (c) summer (June–July–August) and (d) autumn (September–October–November).

We next consider the spatial accuracy of the sea ice model for each season using the difference in root-mean-square error (RMSE) between coupled and uncoupled high-resolution forecasts. We would hope that the use of the sea ice model reduces the RMSE. Figure 7 shows the difference in RMSE at forecast day 10, but we see the same patterns emerging early in the forecast. The dynamic sea ice model shows a general reduction in the RMSE of Arctic sea ice concentration from days 3 to 4 for all seasons.

For summer and autumn, when the persistence assumption is particularly poor, we see improvements from day 2. There are regions where the sea ice model does not show an improvement over persistence. In the central Arctic, this is explained by the verifying analysis, which has complete concentration in the pack ice, whereas the ice model accounts for leads (narrow areas of open water or very thin ice). There are also areas sensitive to SST biases in the ocean model, in the North Atlantic. As expected, the greatest reduction in RMSE is in the summer and autumn, when the ice field changes more rapidly than in winter and spring.

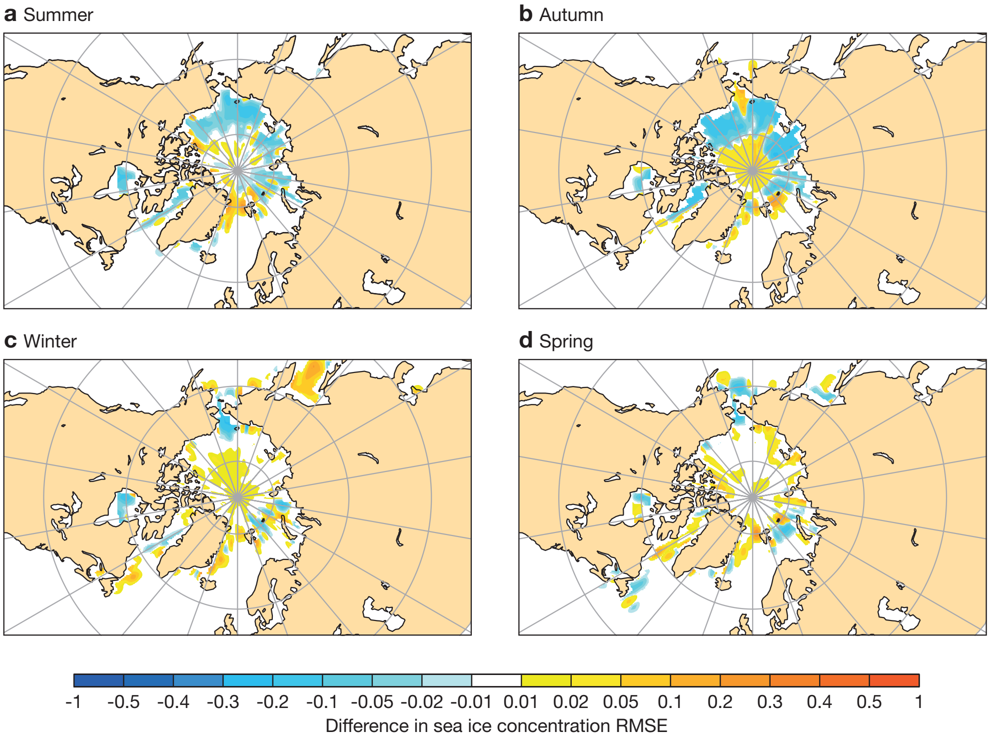

Figure 7 Difference in sea ice concentration RMSE for coupled 10-day HRES forecasts and 10-day HRES forecasts with a persisted ice field (coupled minus persisted), verified against OSTIA for (a) summer (June–July–August), (b) autumn (September–October–November), (c) winter (December–January–February) and (d) spring (March–April–May).

Impact on atmospheric forecasts

The case studies have highlighted how the coupled system allows us to predict the evolution of the sea ice concentration itself. They have also shown that dynamic sea ice leads to local changes in 2-metre temperature forecasts. Another element of interest is the effect of using the dynamic sea ice model on global or hemispheric forecast scores. The first implementation of the sea ice model was within the ensemble system used for medium-range and monthly forecasts. For these forecasts, the effect of implementing the sea ice model on large-scale scores has been shown to be largely neutral. At weeks 3 and 4 there is an improvement in the large-scale circulation in the lower atmosphere and also in 2-metre temperature, but this is not significant. Analysis is ongoing to assess the impact of using the sea ice model on large-scale HRES forecast scores.

Next steps

We have implemented a relatively simple sea ice model which is able to capture the evolution of the sea ice concentration. Work is under way to develop the coupling of the sea ice component and implement a more sophisticated sea ice model, which should improve the prediction of the sea ice evolution, particularly on the long-range time scale.

Further reading

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