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Ocean response to changes in sea ice cover in TOPAZ[1]

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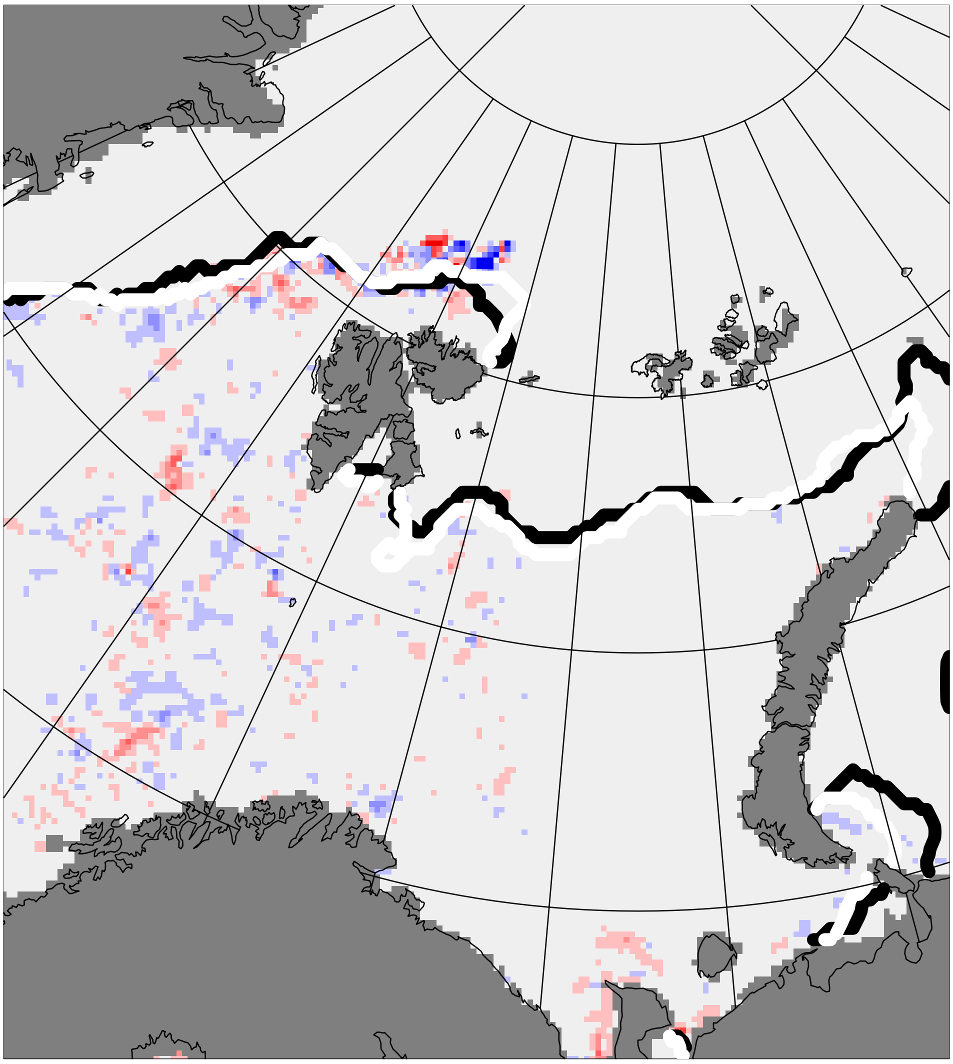

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Abstract Sea ice significantly affects the air-sea heat flux, particularly during winter. The atmospheric model that provides forcing fields for the MyOcean ARC-MFC ocean forecast assumes a fixed sea ice cover. Thus, we investigate how the description of sea ice between the atmosphere and ocean models affect the near-surface properties in the ocean. Weekly model results from 2012 valid for the same dates, produced with a one week offset, are analyzed. Results are classified as values that are decreasing, not changing (or changing minutely), or increasing. We take advantage of results for the sea ice concentration, the position of the ice edge, sea surface temperature and mixed layer depth. We fail to find a deterministic impact on the ocean's surface properies due to changes in the prescribed sea ice conditions invoked in the atmospheric forecasting. We also do not find a relation that distinctly links the evolution in the ocean's surface layer to the local distance to the ice edge. Hence, we conclude that we cannot recommend any changes in the production of ocean forecasts at the ARC-MFC.

Keywords ocean modeling, sea ice, SST, mixed layer depth

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1 Introduction

Sea ice acts as a blanket that insulates the ocean from the atmosphere. Thus, presence of sea ice significantly reduces heat loss from the ocean to the atmosphere during winter conditions in the Arctic, when the temperature contrast between the ocean and the atmosphere may amount to several tens of K. Also, cooling of the atmosphere due to outgoing long-wave radiation effectively keeps the winter-time temperature well below the freezing point of water throughout winter when the heating from the ocean below is low due to the extensive sea ice cover.

With the exceptions of coupled atmosphere – (ice –)ocean configurations, ocean circulation models receives forcing by means of boundary conditions applied at the surface, from atmosphere models or observations. Then, in regions were sea ice may exist, a mismatch between the representation of the sea ice fraction in the atmospheric model and in the ocean – ice model may lead to inconsistencies, particularly in the computation of the imposed heat flux. Conversely, when the forcing is based on observations of the atmosphere, a misrepresentation of the sea ice in the ocean– ice model will again lead to erroneous fluxes.

In this report, results from the TOPAZ model run in a North-Atlantic – Arctic configuration at the MyOcean Arctic Monitoring and Forecasting Centre (ARC-MFC) are examined. In Section 2 the atmospheric forcing and the initialization of sea ice in the model's assimilation step is described. Next, in Section 3 the methods applied in the present study is provided. Then, in Section 5 the results of the analyses of the dependence of the TOPAZ results on the sea ice conditions are presented, and the recommendation is given in Section 6.

2 TOPAZ configuration in MyOcean

The TOPAZ simulations at the ARC-MFC are forced with atmospheric fields from the European Centre for Medium-range Weather Forecasts (ECMWF). The relevant ECMWF model is presently coupled neither to an ocean model, nor to a sea ice model. As a consequence, the sea ice cover is fixed during the forecast period.

The TOPAZ model on the other hand consists of a coupled ocean – sea ice model, *i.e.* the sea ice evolves due to thermodynamic and dynamic forcing throughout the integration period. This gives rise to a mismatch between the representation in the ECMWF model and TOPAZ such as we described in general terms in Section 1.

The TOPAZ simulation schedule is described in detail in Figure 1. Model results and forcing from 2012 are analyzed here. During this period, TOPAZ was in the MyOcean V2 cycle. Note also that the assimilation of sea ice in TOPAZ uses data from the MyOcean Ocean and Sea Ice Thematic Assembly Centre (OSI-TAC). This is not the same product as the sea ice product used by ECMWF, so conditions will be somewhat different even for the same valid day of the two products. These differences are examined in some detail in Section 4.

Note that a modest change in the scheduling took place in June 2012. Figure 1 displays the weekly cycle after the change was implemented. In short, the weekly simulation was performed on Wednesdays prior to June 2012, and the assimilation step was performed for a date which preceded the production date by a week. The shift in the production day from Wednesdays to

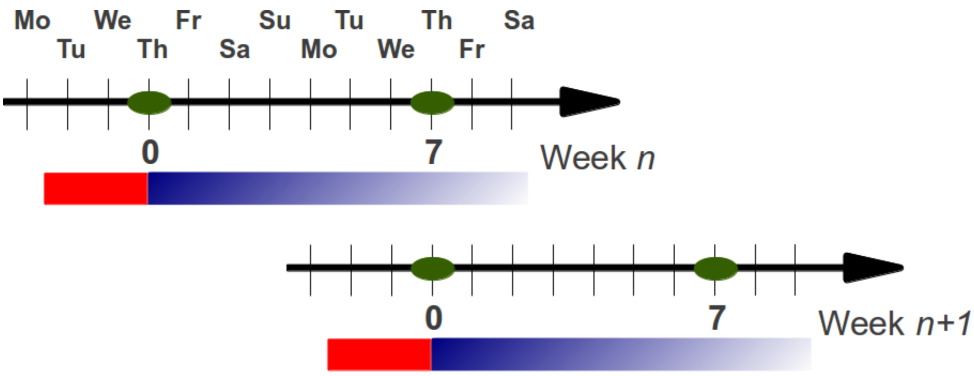

Figure 1: The weekly TOPAZ schedule at ARC-MFC. The time axes are given as the horizontal arrows, with thin vertical lines labelled by the corresponding day at noon. Forecast simulations are performed on Thursday afternoon, and starts with an assimilation step on midnight between Monday and Tuesday. The model simulations uses atmospheric forcing from ECMWF, with analyzed fields up to and including noon on Thursday (red bar), and is continued for 9.5 days with forecasted fields thereafter (blue-grey gradient bar). We consider daily means from Thursdays in this study, indicated by dark green ellipses which are labelled 0 and 7 to indicate the delay relative to the end of the forcing by analyzed atmospheric fields. Shown above are the schedule for two subsequent weeks (labelled "Week *n*" and "Week *n+1*", respectively).

Thursdays in June 2012 has been taken into account in the present analysis.

An overview of the TOPAZ forecasting system is given by Bertino and Lisæter (1, 2008).

3 Methods

We collect daily mean values of selected fields for the days corresponding to labels 0 and 7 in Figure 1 (*i.e.* Thursdays after June 2012). This sets us in position to compare results which are valid for the same day based on TOPAZ simulations from two consecutive weeks. As explained above, the sea ice cover "seen" by the atmosphere model on the same calendar day corresponding to the two simulations will potentially be significantly shifted. On the other hand, the sea ice cover in TOPAZ will adapt to the changing weather conditions, which presumably leads to smaller differences for the same calendar day in the two simulations.

The sea ice concentration (SIC) fields used by ECMWF come with a horizontal resolution of 0.5° x 0.5° in longitude by latitude, while the TOPAZ results for SIC are available on a polar stereographic grid with a resolution of 12.5 km. Hence, the ECMWF SIC fields were interpolated to the TOPAZ grid prior to the analysis, by bi-linear interpolation.

We restrict our analysis to the model sub-domain that is displayed in Figure 2. In this region, the sea ice cover varies substantially throught the year. Furthermore, the sub-domain includes both a shelf sea (the Barents Sea) and a deep sea (the northern part of the Nordic Seas), and there are relatively warm water masses of an Atlantic Ocean origin as well as cold, Polar Water.

We group results in categories, and investigate relation between SIC and changes in the ocean by examination of 2D – matrices where rows and columns give probability distributions derived for the ice cover and oceanic conditions.

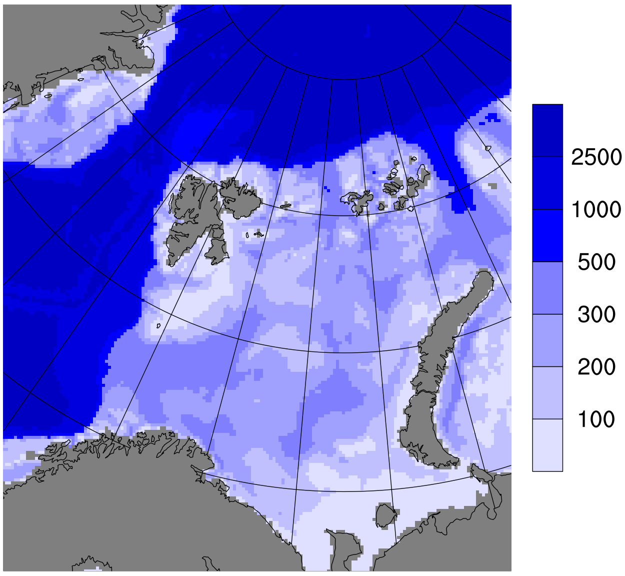

Figure 2: The sub-domain of the ARC-MFC model domain for which results are investigated in the present study. Shown here is filled contours for the bottom topography, with depths in m as displayed by the colour bar to the right. The shelf sea in the centre of this sub-domain is the Barents Sea.

In order to investigate the model sensitivity to the changing ice cover seen by the atmospheric model for the same date, we compute the difference in SIC from the 7 – day forecast (denoted by "7" in "Week *n*" of Figure 1) and the corresponding SIC field that is used at the atmospheric model's analysis time for the forecast that is issued one week later (denoted by "0" in "Week *n+1*").

We first match up categories of changes in SST from the corresponding TOPAZ simulations to the SIC categories. Then, any skewness in the off-diagonal values of the 2D – matrix will be

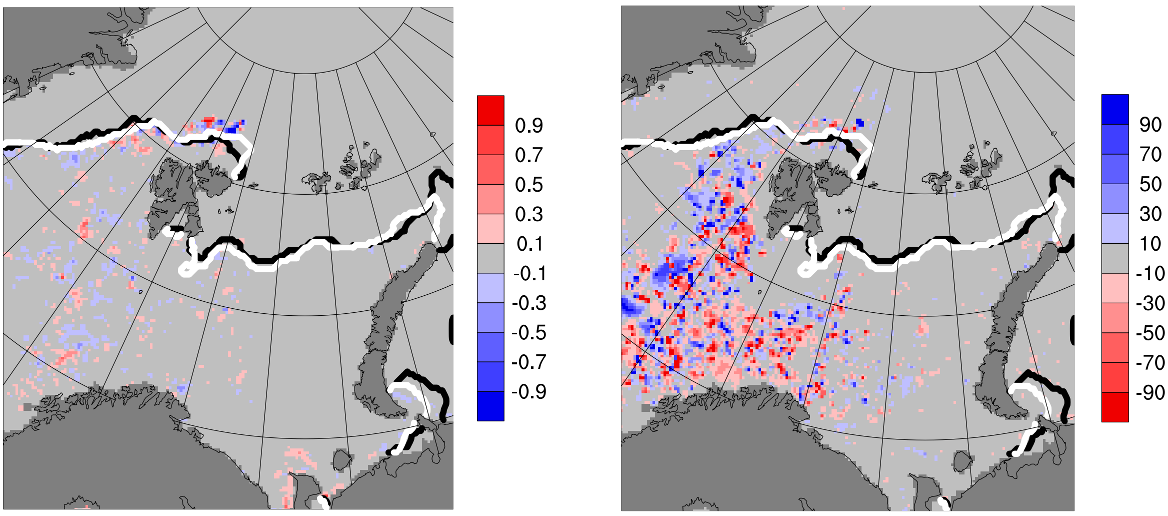

Figure 3: Changes in model results valid on 2012-01-11 from "Week *n* 7" to "Week *n+1* 0". The filled contours in the left and right panels correspond to changes in SST and MLD, respectively. The colour code for the magnitude of changes are displayed by the label bars to the right (in fractions and m, respectively). The ice edges as seen by the atmosphere in the forecasts "Week *n* 7" and "Week *n+1* 0" are displayed as thick black and white lines, respectively.

indicative of biases in SST that arise as a consequence of changing air – sea heat fluxes due to a changing sea ice cover. As an example of this skewness, a local decrease in SIC from “Week *n* 7” to “Week *n+1* 0” might lead to colder SSTs in “Week *n+1* 0” due to an increased loss of heat to the atmosphere, and more rarely to increased SSTs.

However, even if there is an increased loss of heat to the atmosphere as in this example, it may not change the SST at all. This would be the case when the SST is at (or near) the freezing point. Then, heat loss will induce vertical mixing rather than a drop in SSTs. For this reason, we also match up categories of changes in mixed layer depth (MLD) to SIC change categories. In TOPAZ, MLD is defined as the level at which the potential density of sea water exceeds the density of surface waters by 0.03 kg/m^3.

A sample case of the regional distribution of changes in SST and MLD along with the sea ice edges, are depicted in Figure 3. (The sea ice edge is defined as the 0.15 contour of the SIC.) While there seems to be a tendency for relatively large SST changes in the vicinity of the ice edge in the northern Nordic Seas, and the sign of the differences are noisy. Furthermore, the amplitudes of changes in SST and MLD near the ice edge in the Barents Sea is low. However, keep in mind that this is just one sample case, which is included here in order to illustrate the method of our analysis.

4 Sea ice products

As described in Section 1, TOPAZ uses a different sea ice product than the one used by the ECWMF atmospheric forecast model. These products differ by their gridding and by the fact that while the fields used by the atmospheric forecast is time-invariant, this is not the case for the OSI-TAC product. In order to compare the sea ice coverage in these products, one may examine the results in the overlapping region. However, although most of the Arctic is generally covered by the OSI-TAC product, on most days some regions will lack data.

Hence, a comparison of the two products should also be supplemented by an examination of a time-invariant Arctic domain. This is accomplished by extrapolation of the OSI-TAC results over the ECMWF grid by the following algorithm:

1. The region with sea ice in the ECMWF are divided into sub-regions by categories of sea

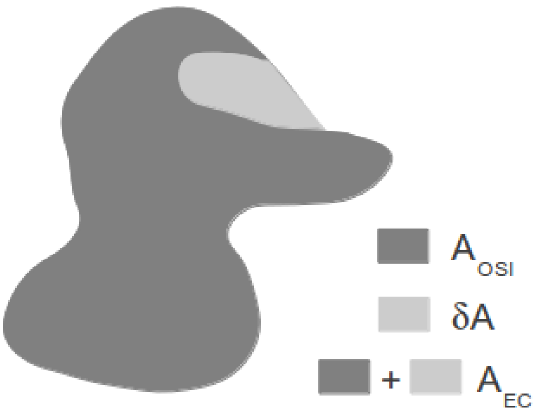

Figure 4: Illustration for ice area from the two products. Shown here is an area of a given sea ice category for the ECMWF product (A_{EC}). The sub-area for which OSI-TAC sea ice data exists, is indicated by A_{OSI}. δA is the region where the sea ice in the ECMWF product falls within the present category, and where there are no OSI-TAC data. See the text for details.

ice coverage. We define the following 11 categories by SIC values: (1): =0, (2): <0,0.1], ..., (11): <0.9,1].

2. Let A^{ice} denote the ice covered area for a category, then the average SIC values for this category becomes
$c_{EC} = A^{ice}_{EC} / A_{EC}$
$c_{OSI} = A^{ice}_{OSI} / A_{OSI}$
$\delta c = \delta A^{ice} / \delta A$
$\hat{c}_{EC} = (A^{ice}_{EC} - \delta A^{ice}) / A_{OSI}$
Here, $\hat{c}_{EC}$ is the average SIC value from the ECMWF product in the region where OSI-TAC data exists.

3. Taking the OSI-TAC product as the base line, the SIC bias in A_{OSI} is
$\Delta c = \hat{c}_{EC} - c_{OSI} = (A^{ice}_{EC} - \delta A^{ice} - A^{ice}_{OSI}) / A_{OSI}$
and we impose the constraint that $\Delta c \leq \delta c$

4. The bias-corrected extrapolation of sea ice data from OSI-TAC for the area of the present category then becomes
$\tilde{A}^{ice}_{OSI} = A^{ice}_{OSI} + (\delta c - \Delta c) \cdot \delta A$

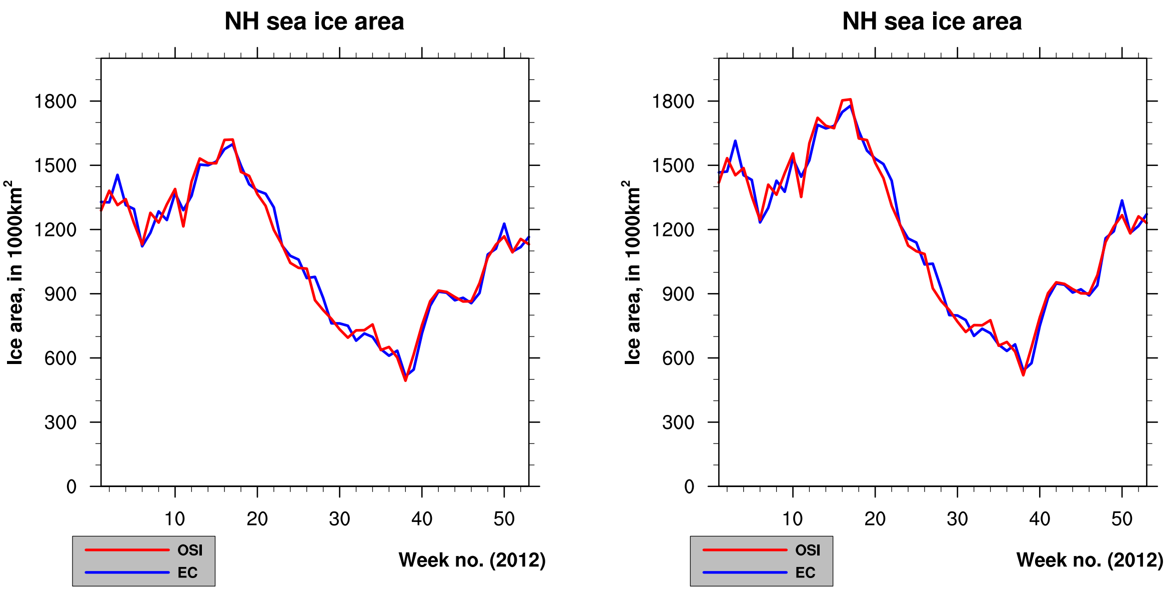

Figure 5: The evolution of the sea ice area during 2012. The sea ice area within the area that at the given date is included in both the ECMWF and OSI-TAC products is displayed in the left panel. The evolution of the sea ice area in the ECMWF domain is shown to the right, after extrapolation of OSI-TAC data as explained in detail in the text. These results are for the domain given by Figure 2.

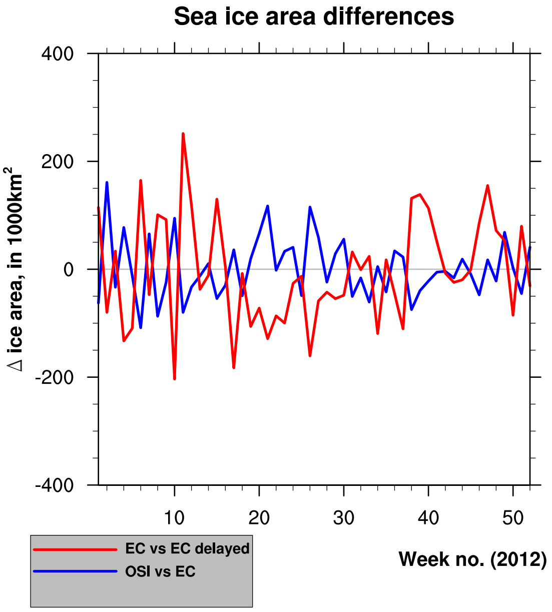

Figure 6: Differences in sea ice area. Shown here are differences on Mondays, which is the week day from which data are collected in the assimilation step of TOPAZ. Differences between the OSI-TAC data and the ECMWF fields are displayed by the blue curve, whereas the red curve show the difference between ECMWF fields with a one week delay.

Next, we compare the temporal evolution of the total sea ice area in the two products. The result is displayed in Figure 5, and we note that the sea ice area is very similar in the two products, regardless if the comparison is restricted to the mutual domain or if extrapolation of OSI-TAC data is used. The only significant discrepancy is seen in the results for week 3.

As explained in Section 2, two TOPAZ forecasts that are valid for the same day, but produced with an offset of one week, will be forced by results from ECMWF weather forecasts which are derived with different specifications of the sea ice cover. In Figure 6 we compare the difference due to a one week delay with the difference between the OSI-TAC data and the ECMWF product.

Although the differences are somewhat larger in the former, they are of similar magnitude as the OSI-TAC *vs.* ECMWF differences. When we restrict the comparison to the melting period (mid-March – mid-September), the average OSI-TAC *vs.* ECMWF difference is 5.000 km^2, while the difference between the one week delayed ECMWF results are -30.000 km^2.

5 Results

We first consider how the surface temperature in the TOPAZ results, valid for the same date, change when the atmospheric forcing has been produced assuming different prescribed sea ice covers. We restrict this analysis to cases where the SIC values have changed by at least 0.05. The results are displayed in Table 1.

We first note that there is a tendency that sea ice fields from the updated atmospheric forecasts have less ice in the melting season, and more ice in the freezing season, as expected. Next, we observe that most of the region where changes in SIC occur, have only negligible changes in SST (74% and 88% in the melting and freezing season, respectively).

The idea that the changes in sea ice cover will have an effect on SSTs due to the change in insulation was particularly expected to have an impact during winter, when the contrasts between

May – June – July

	less ice	more ice
colder	0.10	0.03
no change	0.51	0.23
warmer	0.10	0.02

November – December – January

	less ice	more ice
colder	0.01	0.03
no change	0.36	0.52
warmer	0.04	0.04

Table 1: SST changes as a function of changes in the prescribed sea ice cover applied in the ECMWF atmospheric forecast. Here, **less ice** refers to grids for which there is a reduction of SIC by at least 0.05 in the latest forecast (compared to the forecast issued one week earlier). **more ice** refers to grids with a corresponding SIC increase of 0.05 or more. The temperature changes are from comparisons for the same calendar day. **colder** refers to grids where the updated atmospheric forcing corresponds to SSTs becoming colder by 0.05 K or more, while for **warmer**, the grids have become warmer by 0.05 K or more. The left and right tables are for the seasons with a retreating sea ice cover (May – July) and an expanding cover (November – January), respectively. Numbers are fraction of grids belonging in each category, after grids where the (absolute) change in SIC is below 0.05 are discarded.

SST and the air temperature can become very large. But the results in Table 1 shows that this is not the case.

However, the SSTs in ice infested regions during winter are near the freezing point. Then, due to the possible lack of stability of the water column, rather than a decreased temperature in the regions where sea ice vanishes, the heat loss may give rise to overturning. So we complement our analysis by an examination of how the mixed layer depth (MLD) changes due to variations in the atmospheric model's SIC. The results from this analysis is provided as Table 2.

May – June – July

	less ice	more ice
thinner	0.10	0.06
no change	0.49	0.19
thicker	0.12	0.05

November – December – January

	less ice	more ice
thinner	0.04	0.06
no change	0.31	0.47
thicker	0.05	0.05

Table 2: As Table 1, but now for relations between changes in sea ice and MLD. **thinner** refers to grids where the updated atmospheric forcing corresponds to a thinning of the mixed layer by 5 m or more, while for **thicker**, the mixed layer in grids have become thicker by 5 m or more. Grids where the (absolute) change in SIC is below 0.05 are discarded.

Contrary to our expectations, we find that there is no consistent relation between changes in the atmospheric model's representation of sea ice and MLD during the freezing season. As is the case for SST changes, and again, negligible changes in MLD (68% and 78% in the melting and freezing season, respectively) dominate the statistics.

The relations we have studied this far are not really directly related to forecasting, since the results have been derived assuming an *a priori* knowledge of sea ice conditions one week into a forecast period. In order to provide information that may be utilized in the assimilation step, we next consider how oceanic conditions are related to the local distance to the sea ice edge.

May – June – July

	ocean	MIZ-ocean	MIZ-ice	ice
colder	0.30	0.30	0.21	0.02
no change	0.29	0.34	0.63	0.97
warmer	0.42	0.36	0.16	0.01

November – December – January

	ocean	MIZ-ocean	MIZ-ice	ice
colder	0.32	0.18	0.05	0.00
no change	0.25	0.35	0.87	1.00
warmer	0.43	0.47	0.08	0.00

Table 3: Here, SST changes are defined as for Table 1. The top row indicates categories for the local distance to the ice edge. The definitions are that **ocean** and **ice** are regions that are more than 100 km away from the edge on the open ocean and closed ice sides, respectively, while **MIZ-ocean** and **MIZ-ice** are the respective categories when the distance to the edge is below 100 km. Values represent fractions of occurrence within each ice edge distance category.

We note from the results in Tables 3 and 4 that the evolution of the oceanic conditions are not closely related to the distance to the ice edge. Furthermore, the changes in the ocean on the closed ice side of the edge are minute for both SST and MLD.

The only result that may be of value for the assimilation, is that there is a tendency that the SSTs become warmer on the ocean side, particularly near the ice edge during winter, when updated atmospheric forcing is applied in a subsequent simulation. But even in this case, the sum of the *no change* and *colder* cases exceeds the *warmer* frequency.

6 Conclusions

We can safely conclude from the results provided in Section 5 that although changing sea ice conditions may give rise to anomalous air-sea heat fluxes, there are no relations that can easily be implemented in the assimilation step in order to improve the results from the subsequent simulation.

The present study has been conducted on a basis of well-established relations between air-sea fluxes, sea ice conditions, and their impact on the (near-)surface state in the ocean. Although the background is based on the dynamics and thermodynamics, the study has only taken advantage of purely statistical relations.

So, we are not in a position to determine why there are no clear statistical relations. Nevertheless, we end this study by noting that the changing positions of the sea ice edge, an example

May – June – July

	ocean	**MIZ-ocean**	**MIZ-ice**	**ice**
thinner	0.21	0.18	0.18	0.12
no change	0.53	0.60	0.63	0.78
thicker	0.27	0.22	0.19	0.10

November – December – January

	ocean	**MIZ-ocean**	**MIZ-ice**	**ice**
thinner	0.25	0.21	0.12	0.08
no change	0.52	0.64	0.74	0.86
thicker	0.23	0.15	0.14	0.06

Table 4: As Table 3, but now for relations between changes in sea ice and MLD. Changes in MLD are defined as for Table 2.

of which is displayed in Figure 3, are much smaller than the synoptic scale in the atmosphere. Thus, the change in the forecasted atmospheric conditions for the same day, but issued with a seven day offset, may locally be associated with large variations in the air temperature. Although these changes by no means are the only ones that are relevant in the present context, this atmospheric stochasticity may contribute towards a lack of a simple deterministic oceanic response to the changing sea ice cover used by the atmosphere model.

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