SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Arctic sea-ice, ENSO and seasonal prediction skill in mid-latitude winter circulation
Computer Project Account:	spgbstro
Start Year - End Year :	2021 - 2023
Principal Investigator(s)	Kristian Strommen
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Other Researchers (Name/Affiliation):	Antje Weisheimer (ECMWF) Chris O'Reilly (University of Reading)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The objective was to run seasonal hindcast experiments of the IFS with different prescribed boundary forcings, to examine the relative roles of Barents-Kara sea ice and the El Nino Southern Oscillation (ENSO) at generating skilful seasonal forecasts of the winter North Atlantic Oscillation (NAO). Two experiments would be run. The first would use prescribed boundary forcing (SSTs and ice) from ERA5, except that the sea ice concentration in the Barents-Kara region would be set to 100% every single year of the hindcast (1980-2015). The other would, in a similar manner, suppress interannual variability from ENSO SSTs. Comparison to a control hindcast would allow an attribution of skill.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Several problems were encountered when carrying out the special project. The original proposal for the project suggested to use coupled forecasts, where the initial conditions were altered in place of the boundary forcing. However, after further discussion with experts at ECMWF, it was decided that for sea ice this could have unpredictable side effects and possibly generate model instabilities. It was therefore decided to swap to running the IFS with prescribed boundary forcing. However, the part of the IFS suite allowing for such AMIP-like forecasts was being upgraded, and it took a long time for these to be ready, partially due to Covid. The move to using AMIP-like forecasts also meant that we could no longer compare against the existing coupled control hindcast. It was therefore decided to focus on the role of sea ice alone, and spend extra units creating a control hindcast.

After the first experiments completed, we had some interesting results suggesting sea ice was influencing forecast skill, but also realised that our experimental protocol meant we were possibly underestimating the size of the effect. We therefore requested additional units to run a new experiment in which Barents-Kara sea ice concentration would be set to 0% every year. However, before we had the chance to do this, ECMWF switched to the new Atos computer, and the IFS cycle we had been using (CY47R1) was not ported to Atos and so such experiments could not be done. We therefore opted to request even more units and carried out all 3 experiments (control, 100% ice and 0% ice) on the Atos computer using CY48R1 instead.

While all experiments were eventually satisfactorily, modulo some technical hiccups on the new Atos machine, the analysis has been much delayed as a result, and is still in progress.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

We had a very good experience dealing with ECMWF in all aspects of this project, including advice about requesting additional units and the (as always) excellent technical support.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

We focus in this report on the analysis conducted so far using IFS CY47R1. The comparison with CY48R1 (see Summary of Problems Encountered) has introduced significant additional complexities which we are still trying to understand. We comment on this at the end.

For notation, CTRL denotes the 50-member hindcast run with prescribed boundary forcing (SSTs and ice) from ERA5, while DENIAL denotes the corresponding hindcast where Barents-Kara sea ice concentration is set to 100% every year. There are no other changes in the configuration between CTRL and DENIAL. Both cover 1980-2015, and consist of forecasts initialised on November 1st every year and run through the end of the following February.

Figure 1 shows an example of how the difference in the ensemble mean two-meter temperature (T2M) evolves in November 2009. As expected, the difference is initially strongly localised and centered on the Barents-Kara region. The T2M difference is around 10C early on, and on average between 4 and 5C in the DJF season (not shown).

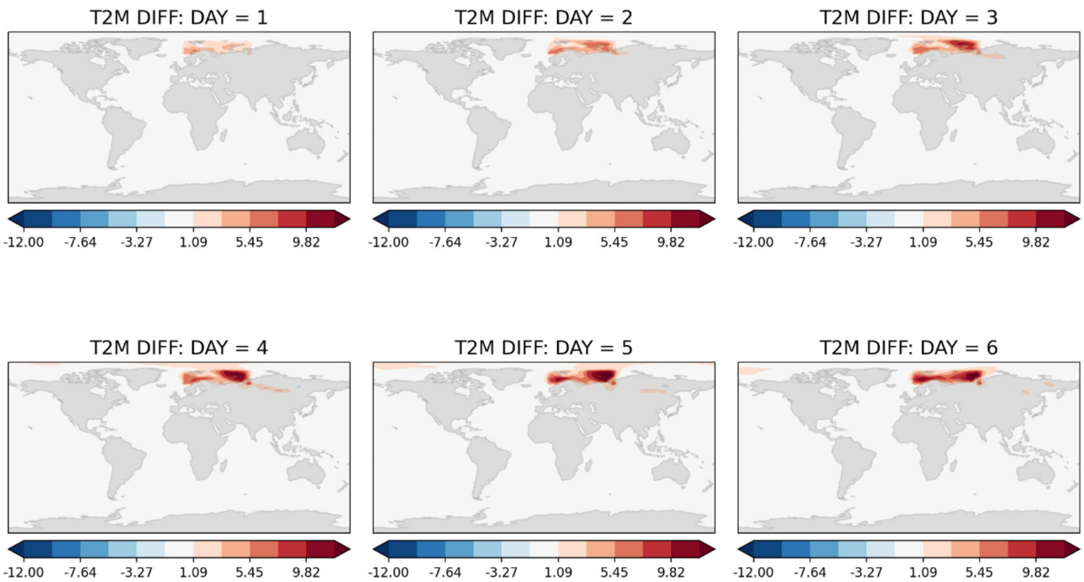

Figure 1: *Difference in ensemble mean two-meter temperature (T2M) between CTRL and DENIAL experiments for the first 6 days of the forecast initialised 2009-11-01.*

Figure 2 similarly shows the evolution of Z500 (geopotential height anomalies at 500hPa) in November 2009. The pressure anomaly starts off local but rapidly spreads across the entire polar region. On average in DJF the Z500 difference clearly projects onto the NAO, as expected (Figure 3). These figures confirm that the experimental protocol worked well and that the IFS forecasts generated the expected NAO signal.

To understand the impact of this signal on forecast skill, Figure 4 shows the NAO timeseries (DJF averages) of ERA5 and the ensemble means of CTRL and DENIAL, along with the associated correlation coefficients. It can be seen that DENIAL has lower skill than CTRL, with the correlation reduced by around 0.15. The p-value for the change was estimated to be almost exactly 0.05 with respect to either a three-way correlation test or a bootstrapping method. Thus we concluded that Barents-Kara is giving some skill to the NAO forecasts, albeit clearly not all of the skill. To understand this better, we followed a strategy proposed by Antje Weisheimer (ECMWF) of looking at the contribution to the ensemble mean correlation from individual years. This is shown in Figure 5. Somewhat surprisingly, the difference is almost entirely concentrated in one year: 2009. This was an extremely negative NAO year which was very well forecast by the IFS, and Barents-Kara sea ice was very anomalously low that year. Suppressing this anomaly, as done in DENIAL, completely removes the skill of the forecast this year, and because of the size of the anomaly, this has a big imprint on the overall ensemble mean correlation.

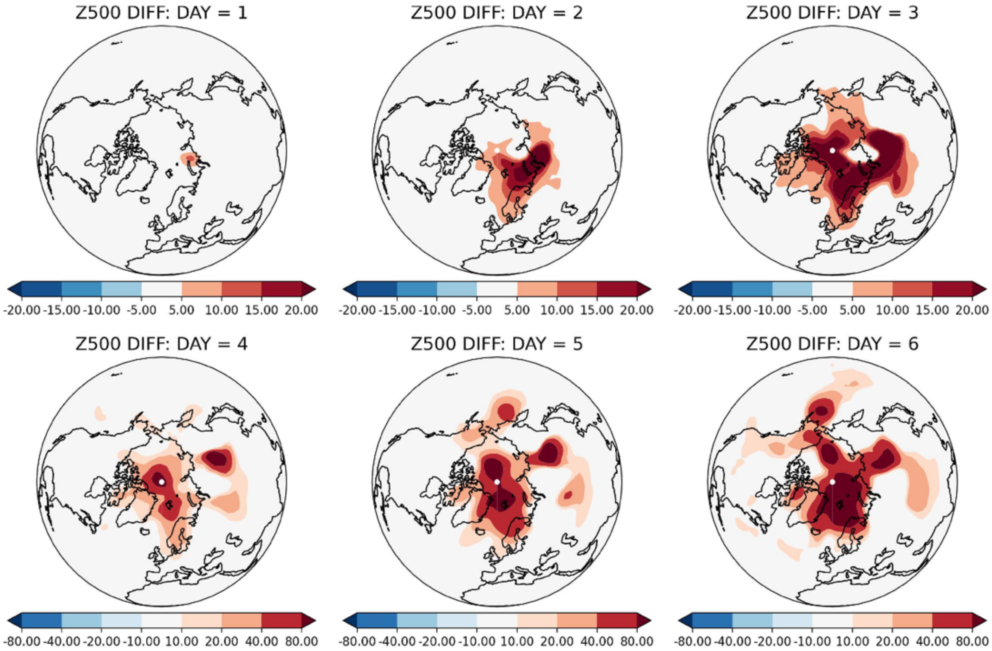

Figure 2: *Difference in ensemble mean Z500 between CTRL and DENIAL experiments for the first 6 days of the forecast initialised 2009-11-01. Note the different scales of the two rows.*

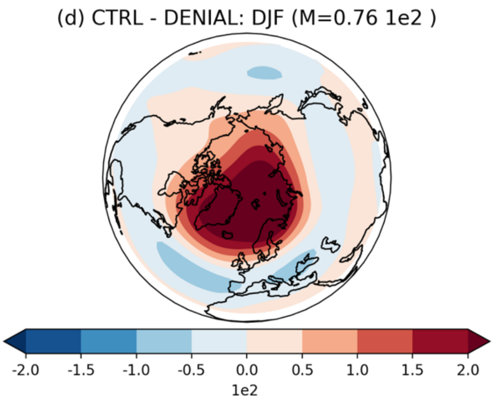

Figure 3: *Difference in ensemble mean Z500 between CTRL and DENIAL experiments averaged across all DJF seasons in 1980-2015.*

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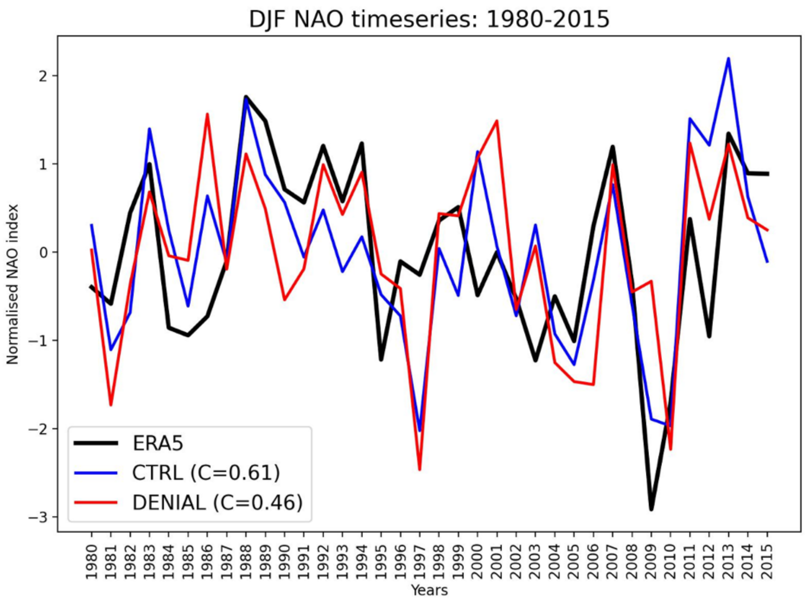

Figure 4: *DJF averaged NAO timeseries for ERA5, CTRL and DENIAL ensemble means. The value of C in the legend denotes the correlation between CTRL (respectively DENIAL) and ERA5. Units have been normalised for visual clarity.*

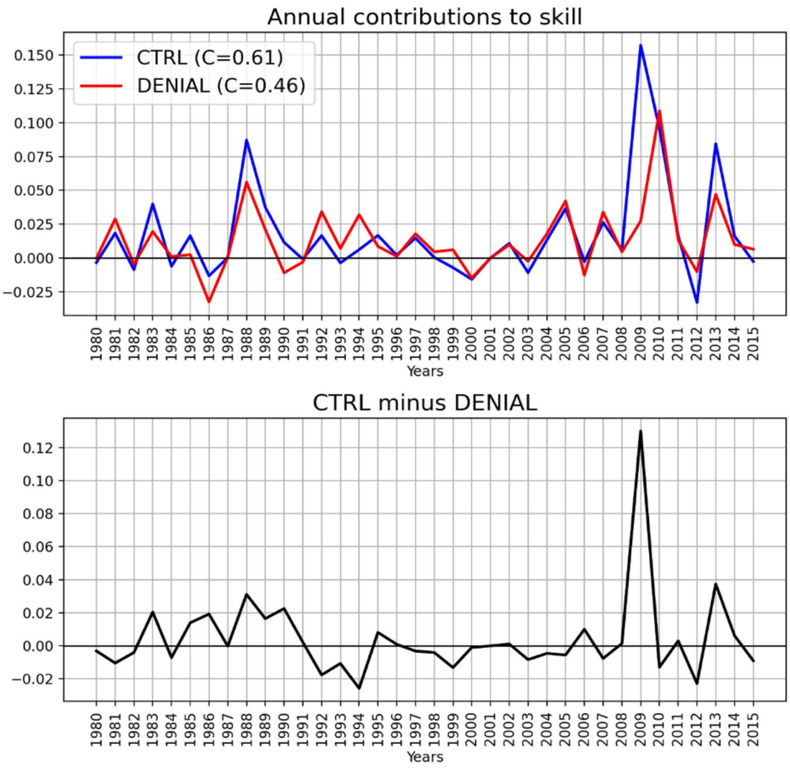

Figure 5: *In (a): contributions of each year to the ensemble mean correlation of CTRL and DENIAL. Hence summing up the blue values gives the total correlation of 0.61 between CTRL and ERA5; similarly for DENIAL. In (b): the difference between CTRL and DENIAL in (a).*

Corroborating this strong intermittency, we found that the overall correlation between November Barents-Kara sea ice and the DJF NAO is approximately zero in both CTRL and DENIAL (not shown). The difference appears to really be concentrated in the single year 2009. Intermittency in Arctic teleconnections has been suggested in previous studies (CITE XXX), though not to our knowledge of such an extreme kind. We therefore began analysing what was special about 2009.

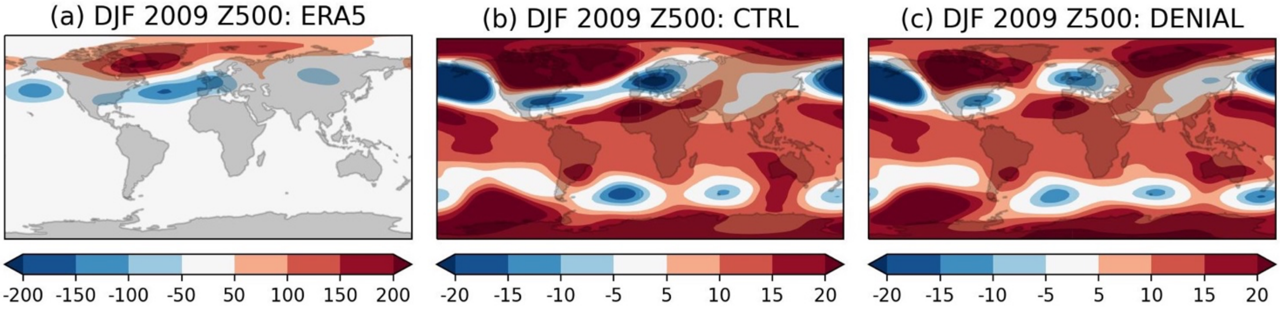

Figure 6: *In (a): the anomalous 2009/10 DJF averaged Z500 in ERA5. In (b) and (c) the same for the CTRL and DENIAL ensemble means. Note the different scales.*

Figure 6 shows what the Z500 pattern looked like in ERA5, CTRL and DENIAL in the winter of 2009/10. In ERA5, the strong negative NAO is apparent, and this is well reproduced by CTRL, together with the strong Aleutian low. In DENIAL, the Aleutian low and Greenland high are well reproduced, but the negative Z500 anomaly extending from the eastern North American continent to Europe (the southern lobe of the NAO pattern) is 'cut off', or 'pinched'. This results in little/no overall projection onto the negative NAO. Similarly, and consistently, while ERA5 and CTRL show a strong, southerly Jetstream, DENIAL shows a weak, split jet (not shown). Figure 7 shows that CTRL has a systematically more negative NAO than DENIAL from around the 10th of December onwards. Throughout most of November CTRL and DENIAL are very similar.

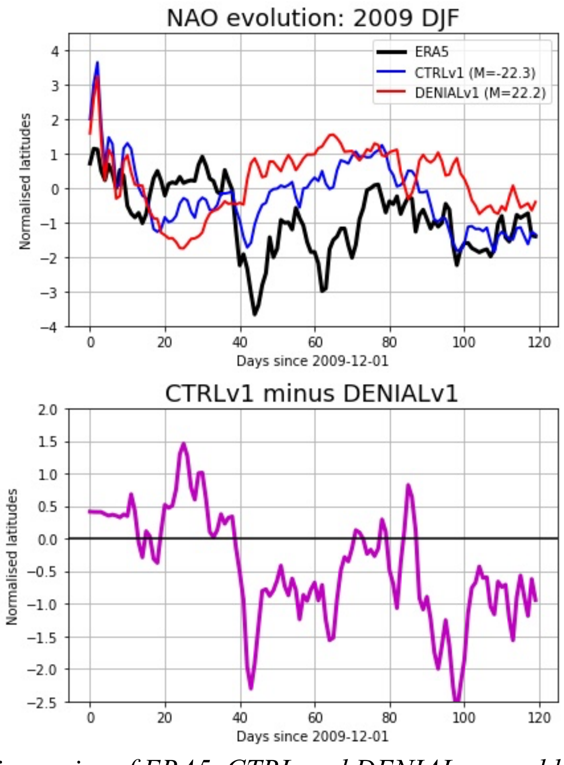

Figure 7: *Top: the daily NAO timeseries of ERA5, CTRL and DENIAL ensemble means, November 1st 2009 to 28th February 2010. Bottom: difference CTRL minus DENIAL.*

We do not yet understand the exact physical pathways involved here. However, we speculate at the moment that the strongly negative NAO this winter may be a tropical signal which is reinforced or amplified by ice-induced thermal forcing from the Barents-Kara region. In the absence of this ice forcing in DENIAL, the tropically forced signal is not allowed to persist beyond November and the two hindcasts begin to diverge. It is possible that the increased divergence seen around day 80 is related to the triggering of a sudden stratospheric warming in the hindcasts, but this has yet to be explored.

Before concluding, we note that the experiments with CY48R1 do not paint a completely similar picture to the above experiments using CY47R1. The skill in the CTRL experiment of CY48R1 is lower (at 0.53 compared to

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0.61), and the contribution from individual years differs somewhat. In particular, the CY48R1 CTRL does not do as good a forecast of 2009, and the difference with the DENIAL experiment is small and not statistically significant. We do not yet know how to interpret these results, and we are currently conducting detailed analysis of the synoptic evolution of the winter 2009/10 across the various experiments. One possibility is that the major updates to the physics parameterisations in CY48R1 (including updates to moist physics and the treatment of snow) have strongly impacted the characteristics of the seasonal forecast in a way which effectively removes the contribution from sea ice in 2009. Another possibility is that the result based on CY47R1 was a strange statistical fluke (i.e., random). Our statistical analysis suggests the possibility of the deviation in 2009 between CTRL and DENIAL in CY47R1 being random is small (<1%), given that the hindcast covers 36 years it could have occurred by chance anyway. We hope to clarify these issues and produce a manuscript explaining the results.

List of publications/reports from the project with complete references

Manuscript is in preparation.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

A new special project application has recently been submitted to carry out the ENSO experiments originally proposed. We hope that besides being interesting in its own right, such an experiment would help put the Arctic experiments in context, especially with regards to the intense intermittency of teleconnections they suggest.