Using NWP to assess the influence of the Arctic atmosphere on mid-latitude weather and climate

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ABSTRACT

The influence of the Arctic atmosphere on Northern Hemisphere mid-latitude tropospheric weather and climate is explored by comparing the skill of two sets of 14-day weather forecast experiments with the ECMWF model with and without relaxation of the Arctic atmosphere towards ERA-Interim reanalysis data during the course of the integration. Two pathways are identified along which the Arctic influences mid-latitude weather, one pronounced one over Asia and Eastern Europe and a secondary one over North America. In general, linkages are found to be strongest (weakest) during boreal winter (summer) when the amplitude of stationary planetary waves over the Northern Hemisphere is strongest (weakest). No discernable Arctic impact is found over the North Atlantic and North Pacific region, which is consistent with predominantly southwesterly flow. An analysis of the flow-dependence of the linkages shows that anomalous northerly flow conditions increase the Arctic influence on mid-latitude weather over the continents. Specifically, an anomalous northerly flow from Kara Sea towards Western Asia leads to cold surface temperature anomalies not only over Western Asia but also over Eastern and Central Europe. Finally, the results of this study are discussed in the light of potential mid-latitude benefits of improved Arctic prediction capabilities.

Keywords: Arctic, atmosphere, relaxation, Northern mid-latitudes, linkage, model

1. Introduction

Due to the rapid Arctic sea ice loss and associated Arctic surface warming, the Arctic and its linkages to the mid-latitudes has received increased interest in the climate research community in recent years, the progress of which is summarized in several review papers (e.g. Overland and Wang 2016; Gao et al. 2015; Vihma 2014; Budikova 2009). Most previous studies are based on either observational data, climate model sensitivity experiments with idealized sea ice conditions or the analysis of data from the Coupled Model Intercomparison Project 5 (CMIP5). While it is difficult to disentangle cause and effect from observations and CMIP5 data, the use of idealized sea ice conditions in models may result in changes of variability and/or inconsistencies along the sea ice edge.

Recently, higher-lower latitude linkages have been investigated from a different perspective by employing a relaxation method (Jung et al. 2014; Semmler et al. 2016). This approach has been originally introduced to diagnose the origin of forecast errors (Jung et al. 2010a) and to investigate causes for the anomalously cold European winters in 2005/06 and 2009/10 (Jung et al. 2010b, 2011). The idea is to run two experiments with a Numerical Weather Prediction (NWP) model: a control forecast experiment using a standard set-up for weather prediction, and another experiment in which the NWP model is relaxed towards reanalysis data in the Arctic. In the relaxation experiment, thus, the observed state is prescribed in the relaxation area. Comparing the relaxation experiment to the standard simulation in which the atmosphere can freely develop everywhere, given a lower boundary forcing, one can diagnose the influence that the atmosphere in the relaxation area has on remote regions. To reduce sampling uncertainty, this has to be done several times in an ensemble approach with different start dates taken from the reanalysis data as initial conditions.

Here, we use the relaxation approach of Jung et al. (2010a) to identify the main atmospheric pathways along which the Arctic atmosphere influences mid-latitude weather and climate. By employing an NWP approach this study will also provide some insight into the potential improvement of medium-range weather forecasting in mid-latitudes that could be obtained by enhancing prediction capabilities in the Arctic (e.g. through an enhanced Arctic observing system). This study is an extension of the work by Jung et al. (2014), which focusses on the winter season and that uses ERA-40 rather than ERA-Interim data (this study) for relaxation, the latter which is of much enhanced quality and covers more recent years. Compared to the previous relaxation experiments in which primarily the mid-troposphere large-scale circulation was investigated, in this study we also consider the impact of tropospheric relaxation on surface parameters which are more socio-economically relevant. Furthermore, we do not restrict our investigation to the winter season. Rather, we consider the seasonal cycle of Arctic-midlatitude linkages and explore possible reasons. Another important difference is the usage of a clearly smaller relaxation area restricted to the Central Arctic.

The outline of the paper is as follows: Details of the experimental setup are given in section 2; this is followed by a decription of the results in section 3. Finally, the outcomes of this study are discussed and conclusions drawn in section 4.

2. Methods

a. Experimental set-up

Numerical experiments were carried out with model cycle 38r1 of the Integrated Forecast System (IFS), which has been run operationally at the European Centre for Medium-Range Weather Forecasting (ECMWF) from 19 June 2012 to 18 November 2013. A spatial resolution of T_L255 was employed, which corresponds to about 0.7°in the horizontal. In the vertical 60 levels were used. Two 14-day forecasts with a time step of 45 minutes were computed for each month between January 1979 and December 2012—the first (second) forecast being initialized on the 1st (15th) day of the month. SST and sea ice fields from the ERA-Interim reanalysis were used as lower boundary condition. ERA-Interim reanalysis data were also used for initialization of the forecast and as a reference when computing forecast errors.

Model results were archived every 6 hours and remapped onto a 2.5°grid.

b. *Relaxation set-up*

To investigate the remote impacts of the Arctic, the development of error during the forecast was artificially reduced by relaxing the model towards reanalysis data in the polar regions north of 75°N (also south of 75°S). This was realized by adding an extra term of the following form to the prognostic equations:

$$-\lambda(\mathbf{x} - \mathbf{x_{ref}}) \tag{1}$$

where $\mathbf{x}$ is the prognostic variable; $\mathbf{x}_{ref}$ is the reanalysis value towards which the model state is drawn; and λ is the relaxation strength parameter. In our study λ assumes a maximum value of 0.1 per time step. This means that every time step the model's tendency is moved towards the reanalysis data by taking 10% of the difference between model result and reanalysis data. To smooth the border of the relaxation area, a hyperbolic tangent over a 20°wide zonal belt was applied. In this region λ increases smoothly from 0 to its maximum value, with the nominal border of the relaxation area in the middle of the 20°belt (for more details see Jung et al. (2010a)). The relaxation was applied in the troposphere up to 300 hPa to zonal and meridional wind components, temperature, and the logarithm of surface pressure.

In this study, two sets of forecasts were produced: one control integration (CTL) without relaxation, and one in which the troposphere is relaxed to ERA-Interim data north of 75°N and south of 75°S (R75). Note that the relaxation has only been applied to the tropospheric prognostic variables described above and not to surface parameters such as sea ice and SST which are prescribed in the same way in CTL and R75, or snow cover which freely develops from the initialization state in both CTL and R75. The difference between CTL and R75 is evaluated in terms of forecast skill in the Arctic and in the Northern mid-latitudes; the influence of the relaxation over Antarctica is described in a companion paper (Semmler et al.

2016). For the time scales considered here, it can be assumed that the relaxation over the Southern Hemisphere has no influence on the Northern Hemisphere and vice versa. This is a reasonable assumption given that a forecast length of 14 days is hardly long enough for possible signals to cross hemispheres.

c. Data analysis

To study the seasonality of the Arctic influence on mid-latitude weather, the year was divided into four seasons: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). In total 204 forecast members were produced for each season. To reduce the noise level, the data were averaged over a time window of 24 hours.

In order to quantify the Arctic impact several mid-latitude (40°N–60°N) regions have been defined:

Europe (EURO): 20°W–40°E

Northern Asia (NEAS): 60°E–120°E

Northern North America (NNAM): 130°W–70°W

These regions were selected because they are highly populated areas which show relatively strong reduction of forecast error due to Arctic relaxation.

d. Composite analysis

To understand whether the Arctic influence is linked to specific atmospheric situations (i.e. flow-dependence), we performed composite analyses for each region considering 500 hPa geopotential height (z500) and mean sea level pressure (MSLP). For each pair of simulations, we considered the difference of the root mean square error (RMSE) between R75 and CTL. We calculated the RMSE using ERA-Interim reanalysis data. We selected forecasts that were improved due to relaxation, considering each time window of 24 hours separately. A forecast was considered to be improved for a particular time window if the error reduction was higher than the limit defined as mean error reduction of the ensemble plus one standard deviation. For the composite of improved forecast members we extracted corresponding reanalysis fields and averaged them. We did the same for the remaining forecast members to form a composite of neutral forecasts. To examine anomalous flow conditions for improved forecasts, we calculated differences between the two composites.

3. Results

a. Arctic influence on mid-latitude prediction skill

The RMSE growth of daily averaged z500 with and without Arctic relaxation, averaged over the entire Northern mid-latitudes, is shown in Fig.1(a). For both integrations (CTL and R75), the error increases strongly during the first 10 days, after which error growth starts to saturate. The same holds for sub-regions of the Northern mid-latitudes (Fig.1(b)–(d)) although there are differences in the magnitude of these values, with the largest values found for Europe (around 180 m) in winter and the smallest ones over Northern Asia (around 120 m in winter). Over Northern North America the values are similar to the average over the entire Northern mid-latitudes. A feature prevailing over the entire Northern mid-latitudes is that summer RMSE values are clearly smaller than winter RMSE values, reflecting the fact that day-to-day variability is much larger for the latter. Spring and autumn RMSE values are only slightly lower than those for winter. Over Europe (Asia) seasonal differences are largest (smallest).

Error reductions depicted in Fig.2 are generally small and amount to around 5% when averaged over the entire Northern mid-latitudes. However, over Northern Asia values are much higher, amounting to about 15% in autumn. In the other seasons, error reductions around 10% are found.

An important question, arising from these results, is why there are such pronounced seasonal and regional differences. To shed light on this issue, it is worth considering the climatological mean flow and its variability. Fig.3(a), (c), (e), and (g) shows z500 climatologies from the ERA-Interim reanalysis data used for the relaxation experiments for different seasons. The meridional gradient of z500 is reduced by about a third in summer compared to winter while spring and autumn take somewhat intermediate values. Furthermore, when taking the standard deviation over all 6-hourly ERA-Interim output intervals per season for each gridpoint, it turns out that there is less variability in summer than in winter (not shown). In addition, the deviation from the zonal mean—that is, the strength of the climatological, stationary planetary waves—is weaker in summer than in winter while spring and autumn are in between (Fig.3(b), (d), (f), and (h)).

Also the regional differences in forecast error and its reduction in Figs. 1 and 2 can be explained by the atmospheric circulation (mean and variability). The large RMSE over Europe compared to the other regions can be explained by the large standard deviation of z500 over this region. When considering the deviation from the zonal mean of z500 (Fig.3(b), (d), (f), and (h)) it becomes obvious that Northern Asia and Northern North America are the areas with northerly components in the mean westerly flow conducive for a large Arctic influence on the mid-latitude weather and climate. For Northern Asia this materialises in the largest RMSE reduction from the relaxation. Interestingly, the same is not true for Northern North America. One possible explanation would be the Pacific influence given the prevailing westerly flow, strong upstream impact from a region known for the importance of mid-latitude dynamics (North Pacific) and the southerly component over the Pacific Ocean (Fig.3(a), (c), (e), and (g)). This may especially influence the western part of the Northern North America region reaching out to 130°W according to our definition.

Figs. 4 and 5 provide a more comprehensive picture of the geographical distribution of the error reduction for the different seasons both in the mid-troposphere (z500) and close to the surface (2 m temperature: t2m). We consider two forecast ranges: Averaging over forecast lead times of 4–7 days, when it is still influenced by the initial conditions and error growth has not saturated yet; and averaging from 8–14 days when the initial conditions play a smaller role and error saturation is much more pronounced.

Figs. 4 and 5 confirm that RMSE reduction due to Arctic relaxation shows some strong regional dependency. Perhaps the most striking feature is the relatively strong Arctic influence over the continents, especially over Asia, compared to the oceans. As mentioned above, this can be explained by the climatological troughs over the east coasts of northern Asia and northern North America, leading to transport of Arctic air into northern Asia and Canada (Fig. 3). As argued by Jung et al. (2014) a possible explanation for a smaller impact over the oceans lies in the fact that the North Atlantic and North Pacific regions are primarily determined by mid-latitude dynamics due to the relatively low-latitude location of the main storm formation regions over the Gulf Stream and Kuroshio regions. Furthermore, from Fig.3(b), (d), (f), and (h) it becomes obvious that over the oceans there is a southerly component in the mean westerly flow leading to a stronger influence from lower latitudes over the oceans.

The Arctic signal propagates southward relatively quickly over Asia. During the second week, for example, RMSE reduction is evident as far south as 20–40°N, although the picture becomes somewhat noisy as we go towards longer forecast lead time due to increased sampling variability. Over Europe and North America only in winter and spring consistent improvements between 5 and 10% are evident for days 4 to 7 and days 8 to 14. During the other seasons, the Arctic impact appears to be smaller and the results are less conclusive in terms of error reduction. The west coasts of North America and Europe, which are marked by maritime climate, show a rather small influence from the Arctic, consistent with the lesser influence over the oceans.

b. Flow-dependence

After having established the existence of preferred pathways along which the Arctic influences mid-latitude weather, it is worth asking whether the strength of this linkage is flow-dependent. Fig. 6 shows z500 anomalies over the Northern Hemisphere that go along with anomalously large improvements in forecast skill over Asia with Arctic relaxation. It turns out that the link is strongest when anomalous northerly flow from the Kara Sea brings air of Arctic origin towards mid-latitudes as can be deduced from positive z500 anomalies over north-eastern Europe and negative z500 anomalies over parts of Asia; this is especially true during boreal winter. It is clearly reflected by a substantial cold anomaly close to the surface in winter (Fig.7). The cold surface anomaly amounts to about 3 K and extends into the Eastern and Central European area because of the z500 anomalies leading to an anomalous easterly flow to the south of the positive z500 anomalies over north-eastern Europe and is accompanied by warm anomalies over the Barents Sea, Greenland and north-eastern North America. The colder European temperatures are consistent with a weaker zonality of the flow which weakens the upstream influence from the North Atlantic. The circulation anomalies are similar to the positive phase of the Eurasia-1 pattern (Barnston and Livezey 1987). In winter the northerly flow anomaly from the Kara Sea into Western Asia is accompanied by a southerly flow anomaly over Eastern Asia as can be deduced from the z500 anomalies in Fig. 6 indicating a weakening of the East Asian winter monsoon.

The character of the flow-dependence for Europe and North America, that is, anomalous northerly flow associated with cold air outbreaks into the considered region increases the linkage, is comparable to that over Asia, at least during winter and spring (not shown). In winter and to some extent in spring unusually skilful forecasts for Europe seem to occur especially in situations with the negative phase of the East Atlantic pattern as defined by Barnston and Livezey (1987). Similarly, like for northern Asia, the anomaly pattern reduces the zonality of the flow and weakens the North Atlantic influence. For northern North America the anomalous flow pattern does not resemble any well-established teleconnection pattern. However, like in the other regions, it is associated with a change in the meridionality of the flow.

4. Discussion and conclusions

While many previous studies investigated the influence of Arctic surface conditions such as sea ice or snow on the large-scale circulation with climate model experiments or observational data, here we identified links between the Arctic and the Northern mid-latitude atmosphere by carrying out NWP experiments with and without relaxation towards reanalysis data in the Arctic atmosphere north of 75°N.

Our Arctic relaxation experiments bring an improvement to forecasts in the Northern mid-latitudes which is largest over continental areas, especially during winter and in Asia. It is reassuring that results are consistent with Jung et al. (2014), despite the clearly smaller relaxation area (north of 75°N instead of north of 70°N). Compared to Jung et al. (2014), it is a new and important result that the Arctic influence is strongest in winter and weakest in summer. Over Asia, reductions of forecast error of up to 15% both in z500 and in t2m could be achieved if one had perfect knowledge of the Arctic atmosphere. Our results, thus, suggest that improved weather predictions in the Arctic (e.g. through an improved observing system) have the potential to improve prediction skill in mid-latitudes over the continents—especially during periods with anomalously northerly flow. In summer the impact of the Arctic over the continental areas is generally weaker due to reduced amplitudes of stationary planetary waves associated with more zonally oriented flow.

Even though our relaxation approach is different from the methods used in most previous studies on the influence of the Arctic on the mid-latitudes and even if we are investigating the influence of the Arctic troposphere as opposed to Arctic surface conditions such as sea ice or snow cover, it is noteworthy that the main pathways identified along which the Arctic can influence midlatitudes are consistent: Previous studies suggest that Siberia tends to be strongest influenced in winter by changes in the Arctic surface conditions such as sea ice concentration and snow especially over the Barents Sea/Kara Sea area and Eurasia but also over the entire Arctic in the preceding summer/autumn (e.g. Honda et al. 2009; Cohen et al. 2012; Francis et al. 2009); Siberia in turn has been identified to be a key region which influences the weather of Northern Europe and to some extent the whole Northern mid-latitudes (Cohen et al. 2012, 2001). Indeed, in cases of a strong pathway from the Kara Sea to Western Asia as indicated by northerly flow anomalies from Kara Sea to Western Asia, cold anomalies over Western Asia extending into Eastern and Central Europe as well as southerly flow anomalies over Eastern Asia indicating a weakening of the East Asian winter monsoon occur, features which have been associated with Barents Sea/Kara Sea ice loss in the preceding autumn (Wu et al. 2015). However, in the present study it is not sea ice loss driving the stronger pathway from Kara Sea to Western Asia as the following consideration indicates.

Given the pronounced loss of Arctic sea ice during recent decades (e.g. Parkinson and Comiso 2013), it is worth asking the question whether associated large scale circulation changes might alter the teleconnectivity and hence the impact that Arctic prediction has on lower latitudes. In this context, a trend towards enhanced meridionality, especially over the continents, could lead to an intensification of the influence of the Arctic atmosphere on the Northern mid-latitudes. Therefore, it could be expected that most of the strongest improved forecasts over Western and Central Asia would occur towards the end of the considered time period from 1979 to 2012. However, in none of the seasons any such trend could be identified over the past 30 years. Therefore, it can be argued that the recent Arctic sea ice loss has not prompted any change in the strength of the influence of the Arctic atmosphere on Northern mid-latitude weather and climate. This also means that we can not confirm previous studies such as Francis and Vavrus (2012) and Tang et al. (2013) linking stronger meridionality in the flow and more extreme cold and hot events with shrinking Arctic sea ice in winter and summer, respectively. It remains to be seen if possible future circulation changes will be large enough to change the strength of the influence that the Arctic atmosphere exerts on the Northern mid-latitudes.

Oceanic areas such as the North Atlantic and the North Pacific as well as the west of North America and Western Europe are less affected by the Arctic, at least on the time scales considered here. It might be argued that this is a result of the relatively southerly location of the jet stream along with a predominantly southwesterly flow, suggesting that instead mid-latitude (and probably also tropical and subtropical) dynamics play a more important role.

Our experiments show that there is scope for improved weather forecasts especially in northern Asia, but to some extent also in north-eastern Europe and northern North America if forecasts can be improved in the Arctic off the Siberian coast and to some extent off the Canadian Arctic coast. In contrast, an improvement of Arctic weather forecast capabilities does not seem to help improving weather forecasts for the western coasts of Europe and North America.

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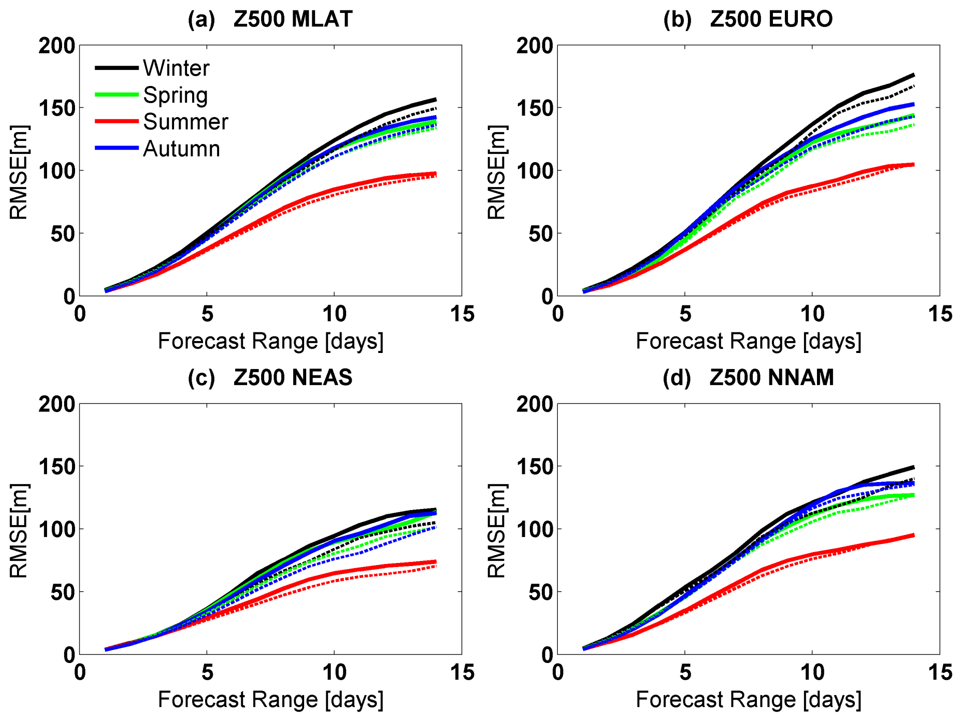

FIG. 1. RMSE of z500 [m] as a function of forecast lead time (in days) for different seasons and forecast experiments (solid line: CTL; dashed line: R75): (a) averaged over the whole Northern mid-latitudes between 40°N and 60°N (MLAT), (b) averaged over Europe (40°N to 60°N, 20°W to 40°E, EURO), (c) averaged over Northern Asia (40°N to 60°N, 60°E to 120°E, NEAS), (d) averaged over Northern North America (40°N to 60°N, 130°W to 70°W, NNAM)

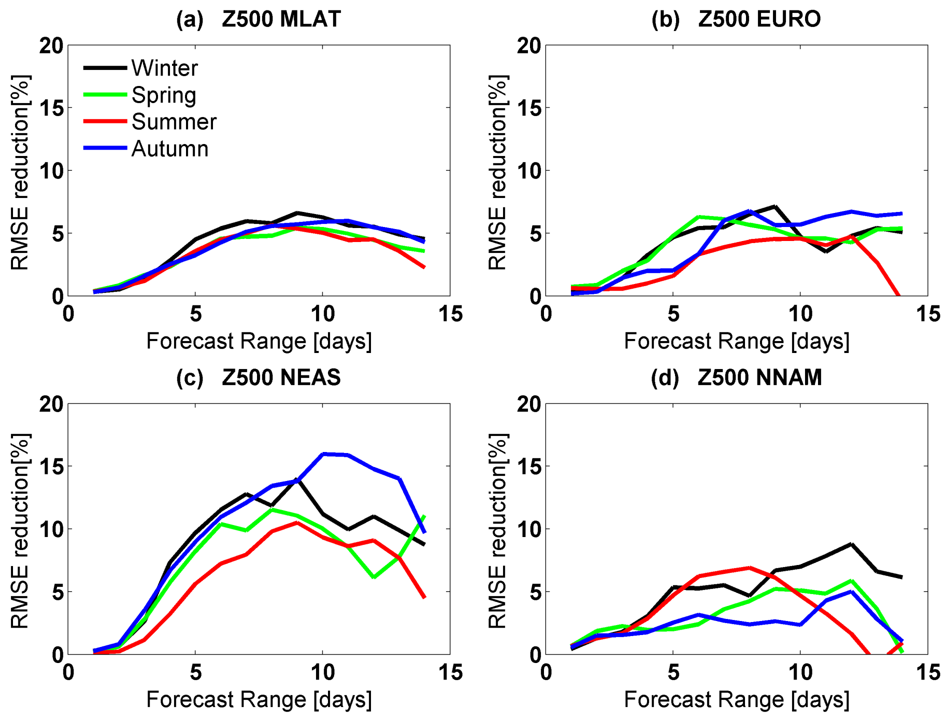

FIG. 2. RMSE reduction [%] of z500 forecasts due to Arctic relaxation as a function of forecast lead time (in days) for different seasons and regions: (a) averaged over the whole Northern mid-latitudes between 40°N and 60°N (MLAT), (b) averaged over Europe (40°N to 60°N, 20°W to 40°E, EURO), (c) averaged over Northern Asia (40°N to 60°N, 60°E to 120°E, NEAS), (d) averaged over Northern North America (40°N to 60°N, 130°W to 70°W, NNAM)

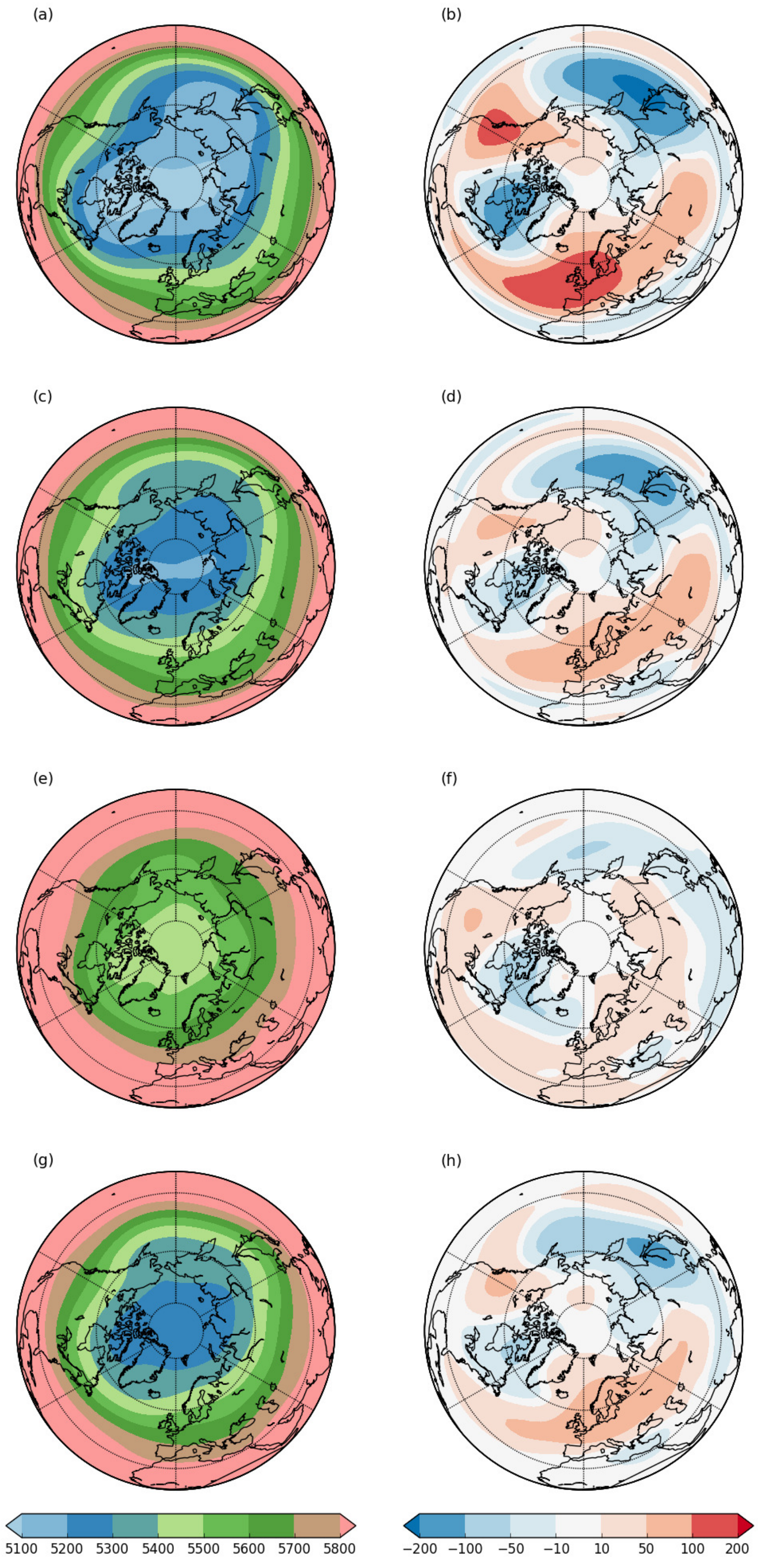

Fig. 3. z500 [m] from the ERA-INTERIM data used for the relaxation: (a) winter mean, (b) mean stationary wave field (deviation from zonal averages) for winter, (c) and (d) as (a) and (b) but for spring, (e) and (f) for summer, and (g) and (h) for autumn.

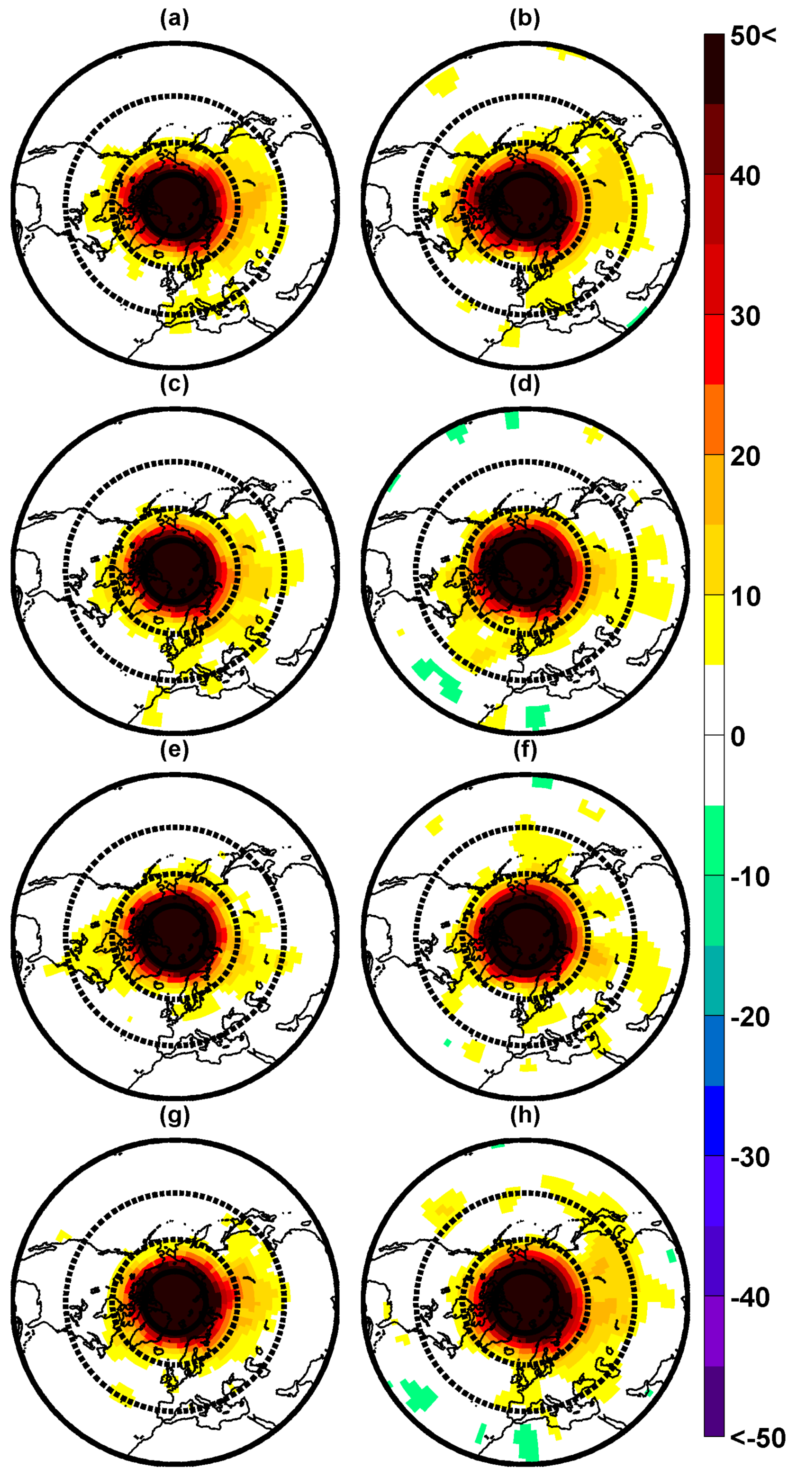

Fig. 4. RMSE reduction [%] of the z500 forecasts for the Northern Hemisphere north of 20°N due to Arctic relaxation and for different seasons: (a) winter averages over forecast lead times 4 to 7 days, (b) winter averages over forecast lead times 8 to 14 days, (c) and (d) as (a) and (b) but spring, (e) and (f) summer, and (g) and (h) autumn. The dashed lines indicate the Northern mid-latitude region from 40°N to 60°N.

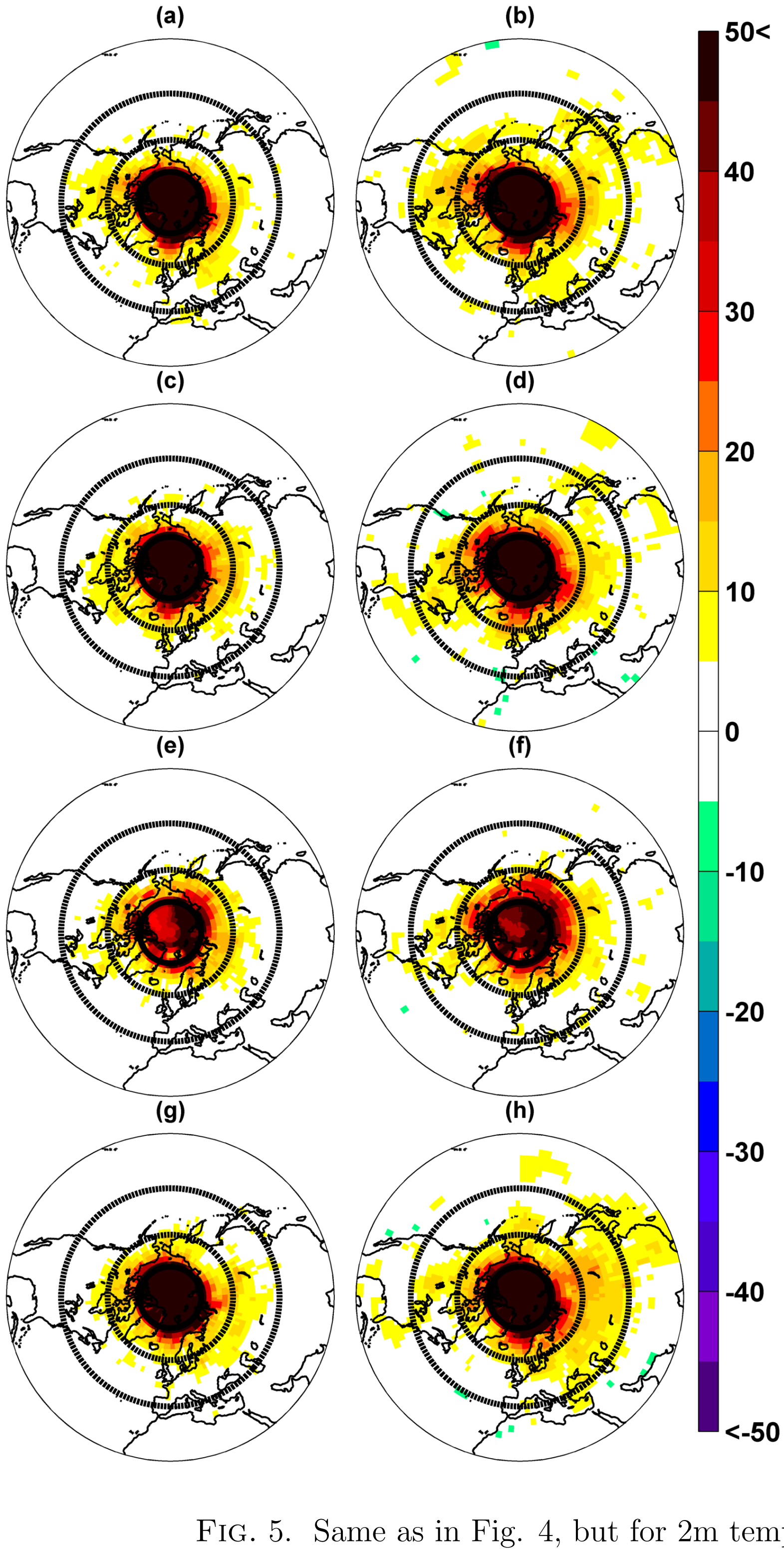

Fig. 5. Same as in Fig. 4, but for 2m temperature forecasts.

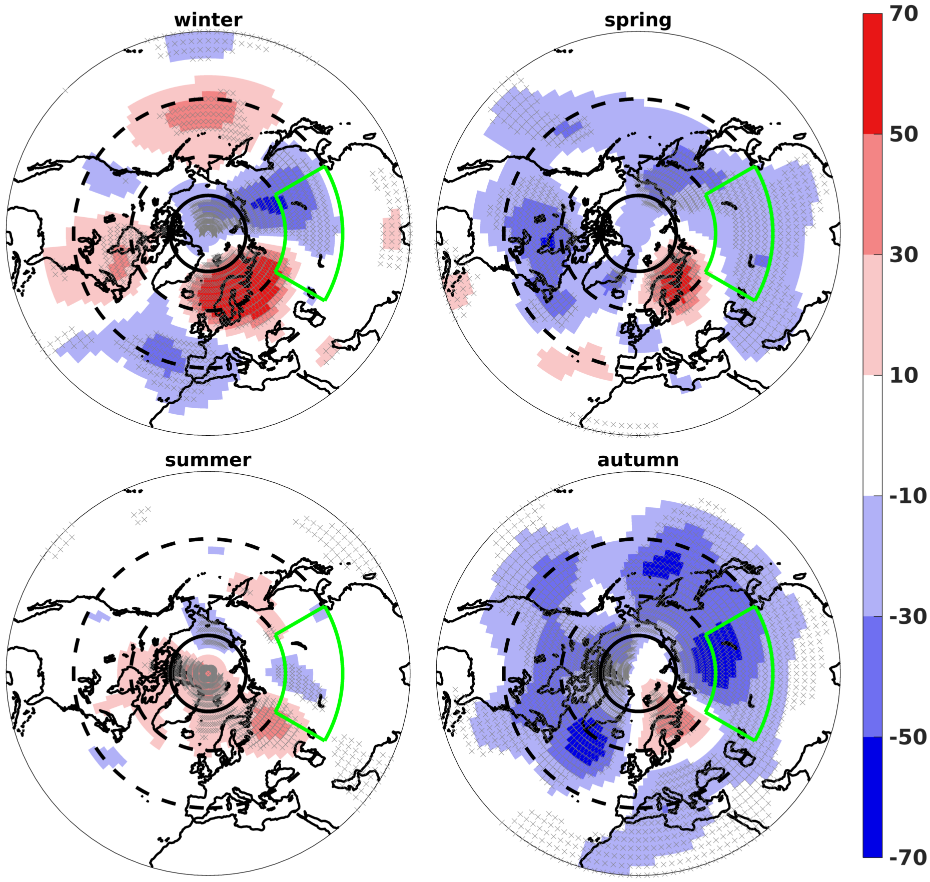

FIG. 6. z500 difference [m] between mean composites for improved and neutral forecasts with Arctic relaxation for Northern Asia (green box) considering forecast lead times 1 to 7 days. Stippled areas indicate areas significant according to a Wilcoxon test.

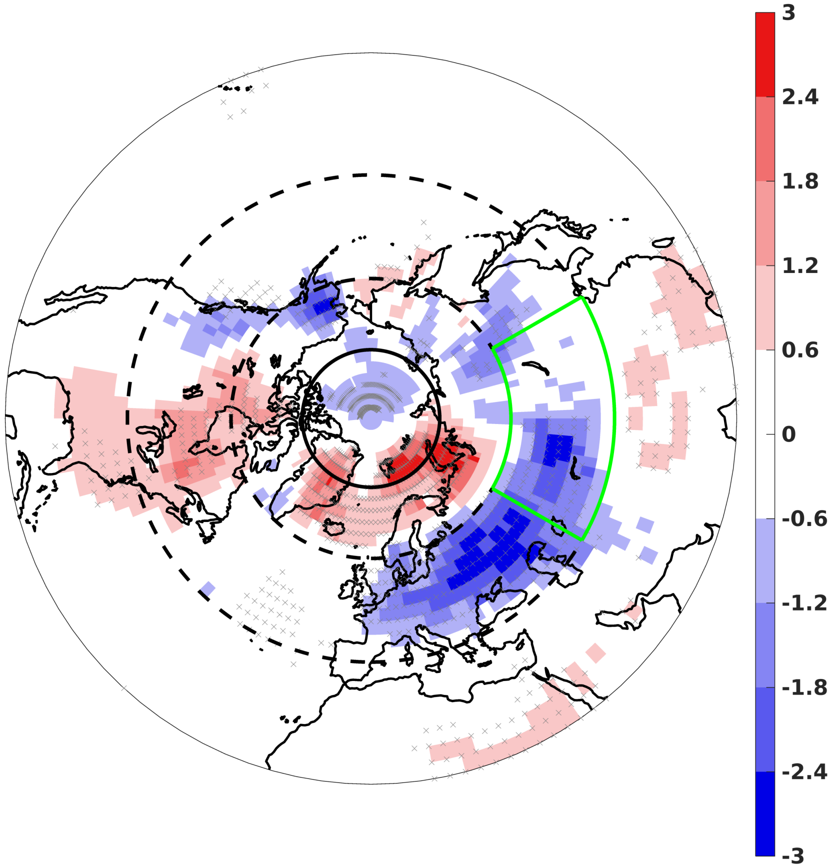

FIG. 7. t2m difference [K] between mean composites for improved and neutral forecasts (with respect to z500) with Arctic relaxation for Northern Asia (green box) for winter considering forecast lead times 1 to 7 days. Stippled areas indicate areas significant according to a Wilcoxon test.