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Impacts of the Arctic-midlatitude teleconnection on wintertime seasonal climate forecasts

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Abstract

The impact of the Arctic on midlatitude weather and climate is still in scientific debate. The observation-based analysis, however, shows frequent concurrences of Arctic warming with extreme cold in the midlatitudes, and vice versa. This teleconnection could aid in seasonal climate forecasts for the midlatitudes. This study assessed the forecast skill of Arctic temperature and the Arctic-midlatitude teleconnection patterns in operational seasonal climate forecast models based on their wintertime forecast archives. Further, the impact of the Arctic-midlatitude teleconnection on the midlatitude forecast skill is evaluated. The results revealed that most climate forecast models have the capability to simulate the overall pattern of Arctic-midlatitude teleconnection for both the eastern Eurasian and North American regions. However, this is little converted to practical forecast skill in midlatitude likely due to poor capabilities in forecasting Arctic temperatures. Idealized analysis (assuming a perfect forecast of Arctic temperature) showed that considerable forecasting improvements could be achieved, and further improvements are possible with accurate simulations of the Arctic and its teleconnection patterns. These results highlight the importance of better predictions of the Arctic conditions in seasonal forecasts that are not just limited to their own region but extend to midlatitude weather and climate as well.

1. Introduction

There have been significant advances in seasonal dynamic prediction capabilities with tremendous improvements in climate modelling science and extensive increases in observational data over the last few decades (Cane *et al* 1986, Tn *et al* 2010). Notably, tropical ocean variabilities like the El-Niño Southern Oscillation (ENSO) which now can be predicted earlier than one season ahead provide forecast skill over midlatitude where the tropics-midlatitude teleconnection has direct impacts on weather and climate variabilities (Palmer *et al* 2004, Wang *et al* 2009, Doblas-Reyes *et al* 2013). In addition to ENSO, it has been widely recognized that Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO) provide forecast skill for midlatitude climates on an intraseasonal to interannual time-scale (Palmer *et al*

2004, Doblas-Reyes *et al* 2013). However, such tropical influences are pronounced especially over the midlatitude ocean, and there is limited skill over most continental midlatitudes where the tropical influence is less significant and indirect (Oldenborgh *et al* 2005, Lee *et al* 2013). Therefore further predictive skill improvements have been sought by using other longer-timescale boundary conditions like soil moisture (Koster *et al* 2006, 2010), snow (Jeong *et al* 2013, Sospedra-Alfonso and Merryfield 2018, Tseng *et al* 2018), sea-ice (Day *et al* 2014), and stratospheric disturbances (Scaife *et al* 2016), or by applying post-processing to model predictions like a multi-model ensemble (MME) (Kug *et al* 2008, Ahn and Lee 2016).

Recently, it has been suggested that Arctic sea ice or Arctic climate variabilities could be alternative factors that could affect mid-latitude weather and climate (Day *et al* 2014, Cohen *et al* 2020). Despite the

continued global warming trend, severe cold winters have occurred frequently in the northern extratropics in recent decades (Guirguis *et al* 2011, Cohen *et al* 2012, Coumou and Rahmstorf 2012), and most of the prediction models had great difficulty forecasting such extremes (Shin and Moon 2018). The rapid seasonal warming of the Arctic associated with autumn sea-ice loss is regarded as one of the primary causes of these harsh cold winters (Li and Wang 2012, Pedersen *et al* 2016, Serreze *et al* 2009, Sohn *et al* 2011, Wang *et al* 2017a). Sea-ice reduction and associated energy flux change were suggested to alter atmospheric circulation that could bring cold air to the extratropics via a Rossby wave propagation or stratospheric feedback (Honda *et al* 2009, Kim *et al* 2014, Meleshko *et al* 2016, Petoukhov and Semenov 2010, Wang *et al* 2017b). Some other studies, however, have suggested that the recent cold winters were not induced primarily by sea ice loss. For instance, Blackport *et al* (2019) and Fyfe (2019) suggested that the Arctic sea ice reduction was not the root cause of the midlatitude cold. They argued that large-scale atmospheric circulation drove Arctic sea ice loss and midlatitude cooling simultaneously. On the other hand, Matsumura and Kosaka (2019) and Wang *et al* (2018) argued that the tropical ocean variabilities induced the Arctic sea ice loss and Eurasian cold winters.

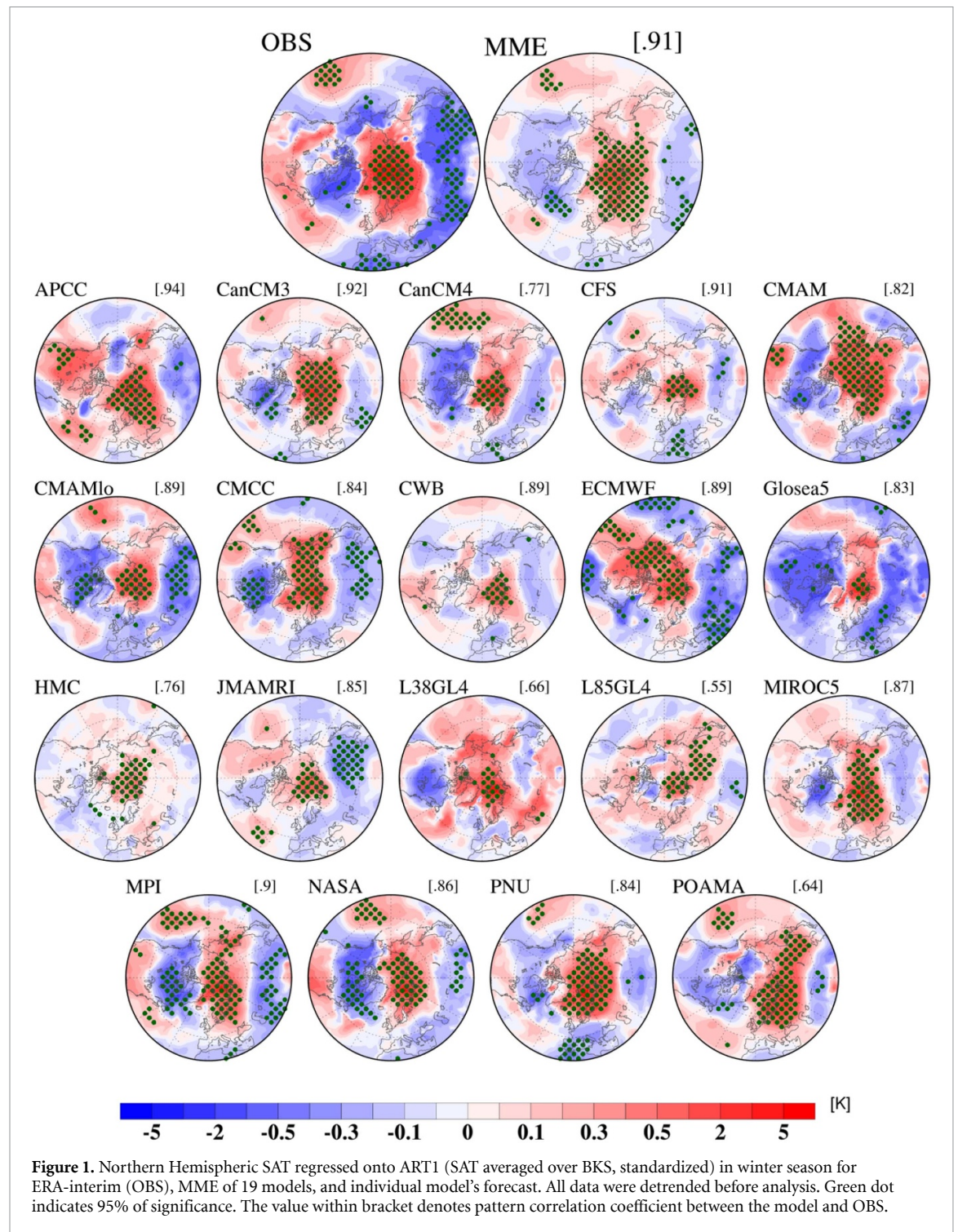
Though the causality between Arctic sea-ice loss and midlatitude cold winters is still debatable, observational analysis consistently shows an inverse correlation between the Arctic and midlatitude temperatures, and, even more, pronounced, a concurrence of warmer Arctic and cold mid-latitude temperatures (Liu *et al* 2012, Kug *et al* 2015, Overland *et al* 2015, Cohen *et al* 2020). Across the Eurasian region, this phenomenon is called ‘warm Arctic–cold Siberia’ (WACS) or ‘warm Arctic–cold Eurasia (WACE)’ (Overland *et al* 2011). This occurrence is also seen over the Pacific sector of the Arctic and North America with a few days to weeks of delay (Kug *et al* 2015, Song and Wu 2018, Lü *et al* 2019). Recalling that the skill harvested from the tropics–midlatitudes teleconnection is a primary source of seasonal forecast skill for the midlatitudes, we may expect the same with the Arctic–midlatitude relationship if the Arctic can be predictable to the same extent as tropical ocean surface temperatures. Air temperatures over the Arctic region are extensively affected by turbulent heat fluxes from the ocean, which are particularly affected by the summer–fall climate conditions of sea-surface temperatures in the Arctic (Serreze *et al* 2009, Screen and Simmonds 2010, Kurtz *et al* 2011) as well as influences from extratropics and tropics (Ding *et al* 2014, 2017). Though complicated mechanisms are involved, precise data collection and analysis of sea-ice and oceanic conditions along with an accurate simulation of atmospheric–ocean interactions in climate models may allow for the improvement of forecast

capabilities involving Arctic temperature. Due to limited data and research on the Arctic climate system, climate prediction models do not include realistic initialization of Arctic sea ice (Morioka *et al* 2019), which have a significant effect on the Arctic (Wang *et al* 2013). Additionally, relatively little research has been done on the effect of Arctic regional variability on the Arctic–midlatitude teleconnection and dynamical seasonal predictions (DSPs). Jung *et al* (2014) showed that improved forecast of Arctic troposphere could provide enhanced skill for sub-seasonal midlatitude prediction based on the forecast experiments with the ECMWF (European Centre for Medium-Range Weather Forecasts) model with and without relaxation of the Arctic troposphere toward reanalysis data. Lawrence *et al* (2019) also showed similar influences with the ECMWF numerical weather prediction model by performing forecasts with and without Arctic observation data. Even though the potential usefulness of Arctic–midlatitude teleconnection has been recognized by previous studies based on idealized experiments (Mori *et al* 2014, Kug *et al* 2015), the results on the impacts in real-world scenarios of an operational seasonal forecast model are still lacking. Moreover, the MME approach becomes more common for DSP like NMME (North American Multi-Model Ensemble; Kirtman *et al* 2014), LC-LRFMME (Long-Range Forecast Multi-Model Ensemble; Min *et al* 2009), and APCC MME (APEC Climate Center Multi-model Ensemble; Min *et al* 2017), so it will be useful to investigate potential forecast skill achieved by the Arctic–midlatitude linkage in different forecast models and their MME.

In this study, we investigated the extent by which the Arctic–midlatitude teleconnection affects DSP of surface air temperature (Kirtman *et al* 2014) in the Northern Hemispheric during winter season. An extensive archive of climate forecasts/hindcasts from 19 operational climate prediction models was utilized. We first examined the general performance of climate forecast models to simulate the Arctic–midlatitude teleconnection and the Arctic temperature. Then we tried to quantify the extent to which the seasonal prediction skill for the midlatitudes could be improved by utilizing the Arctic–midlatitude teleconnection.

2. Data and methods

This study used an archive of 19 different seasonal forecast models, which consist of 13 models provided by the Climate-system Historical Forecast Project (CHFP; Kirtman and Pirani 2009) initiated by the World Climate Research Program, and six models used for a MME seasonal forecast by the APCC as listed in table 1. We analyzed all available models when the analysis was done. Winter (December to February) mean SAT from the forecasts initialized



on November 1 was analyzed to examine the seasonal forecast skill of the models. This study used the anomaly correlation coefficient (ACC) between the forecasted and observed SATs as a metric for forecast skill.

The CHFP dataset is a historical archive of forecasts produced by the modelling system at the initialized time that the prediction was produced. Therefore, the modelling system could change over time. On the other hand, the APCC dataset consisted of reforecasts or retrospective forecasts from a fixed

version of the model at the time that the most recent prediction was produced. The archived forecasts covered the period of 1979–2014 but varied in length from 16 to 34 years, depending on the model. To utilize maximum samples as much as possible, models' forecasts for all available years were used regardless of the period difference. Consequently, climatology and anomaly were calculated for the data available period for each chosen model. However, results from the climatology calculated for the period 1980–2011, when the data of the most models is

Table 1. Brief summary of forecast and hindcast datasets.

Model	Subset	Period	Sea ice	Ens. size
(1) APCC	APCC	1983–2014	Interactive sea ice	5
(2) Cn-CM3	CHFP	1979–2008	Interactive sea ice	10
(3) Cn-CM4	CHFP	1979–2008	Interactive sea ice	10
(4) CFS	CHFP	1981–2006	Prescribed sea ice (climatology)	7
(5) CMAM	CHFP	1979–2008	Prescribed sea ice (climatology)	10
(6) CMAMlo	CHFP	1979–2008	Prescribed sea ice (climatology)	10
(7) CMCC	APCC	1981–2005	Prescribed sea ice (climatology)	9
(8) CWB	APCC	1981–2005	Prescribed sea ice (climatology)	10
(9) ECMWF	CHFP	1981–2010	Prescribed sea ice (previous 5 year sampled)	15
(10) GloSea5	CHFP	1996–2009	Interactive sea ice	25
(11) HMC	APCC	1983–2014	Prescribed sea ice (climatology)	10
(12) JMAMRI	CHFP	1979–2010	Prescribed sea ice (climatology)	10
(13) L38GloSea4	CHFP	1989–2002	Interactive sea ice	9
(14) L85GloSea4	CHFP	1989–2009	Interactive sea ice	9
(15) MIROC5	CHFP	1979–2011	Interactive sea ice	8
(16) MPI	CHFP	1982–2011	Interactive sea ice	9
(17) NASA	APCC	1982–2012	Interactive sea ice	11
(18) PNU	APCC	1980–2010	Interactive sea ice	5
(19) POAMA	CHFP	1980–2009	Prescribed sea ice (climatology)	10

available, do not much different from the suggested. The number of ensembles ranged from 5–25 per model, and the simple ensemble average for each model was used.

The 19 prediction models had their own initialization methods. Table 1 summarizes the key characteristics of each modelling system. Only about half of the modelling systems had an interactive sea-ice model or scheme. Many of the models used the prescribed sea-ice levels based on either climatology or data on recent conditions. In this case, predictions for the Arctic sea ice region relied on variability outside the Arctic or indirect effects from the Arctic Ocean below. Since the CHFP is a historical archive of forecasts, some models may have differed in their past and current sea-ice models and initialization techniques.

The SAT from ERA-interim (Dee *et al* 2011), interpolated to the target model's resolution, was used as a substitute for observation to measure forecast skills. The ERA-interim is one of the best reanalyses in terms of the quality of Arctic surface temperature (Lindsay *et al* 2014), though it has a slight wintertime warm bias over sea ice (Simmons and Poli 2015).

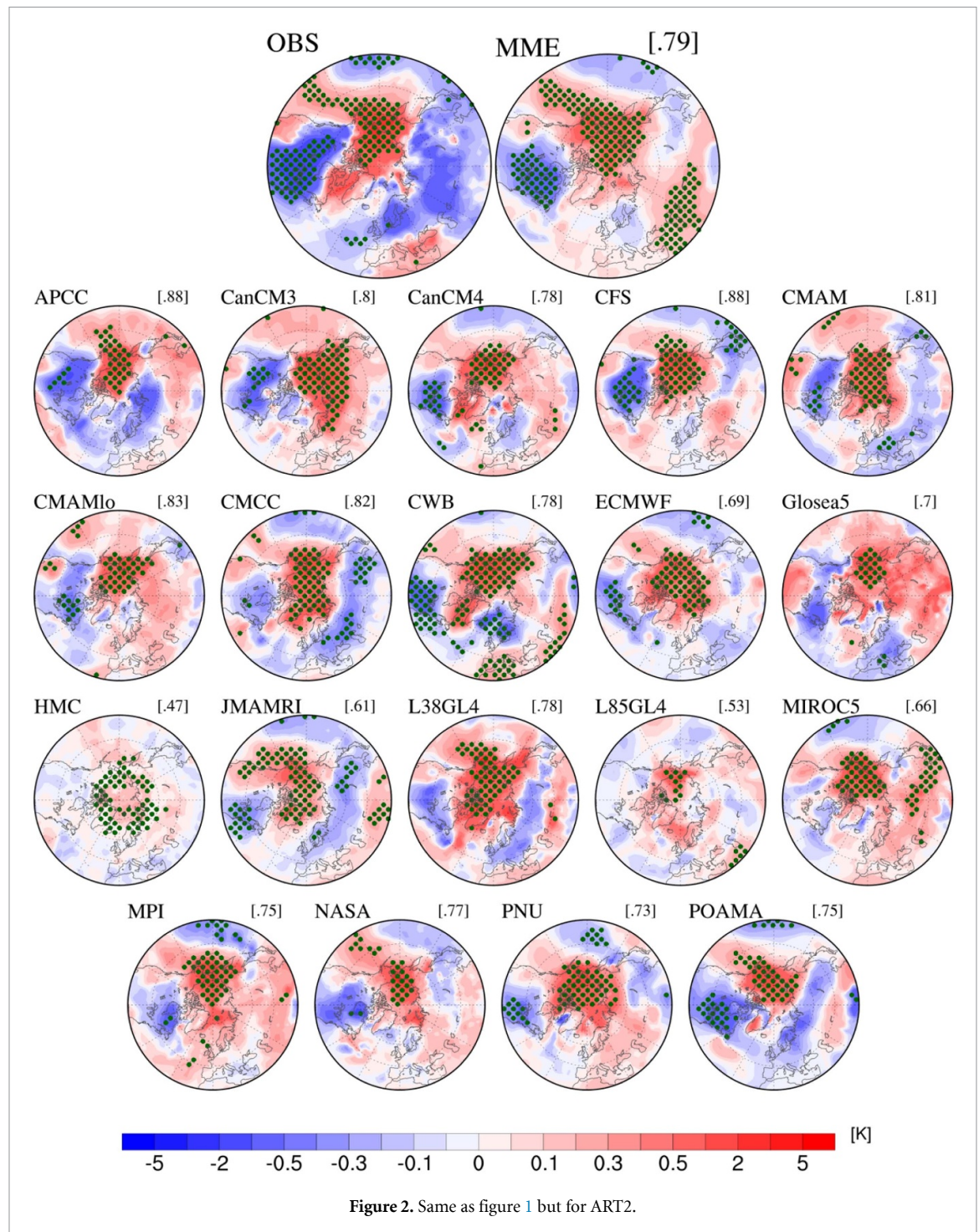
To represent the Arctic-midlatitude teleconnection, two indices representing regional temperatures in the Arctic were utilized. Kug *et al* (2015) suggested that there are two distinct patterns in the Arctic-midlatitude teleconnection originating in the Arctic region. The two Arctic regions studied were the Barents-Kara Sea (BKS: 70–80°N, 30–70°E) and the East Siberian-Chukchi Sea (ECS: 65–80°N, 160°E–160°W). The SATs, which were averaged across the two regions, hereafter referred to as ART1 and ART2 following Kug *et al* (2015), correlated negatively with the temperature of East Continental Eurasia (−0.36) and continental North America (−0.70).

3. Results

3.1. Arctic-midlatitude teleconnection simulated by the models

We first examined the forecast models' capabilities to simulate the Arctic-midlatitude teleconnection. Figures 1 and 2 represent the linear regression of ART1 and ART2, respectively, on SATs over the Northern Hemisphere (north of 30°N) in the 19 models' forecasts, their MME, and observational data (the ERA-interim). The MME was calculated by using available models in each year for the entire period 1979–2014. The analysis was done with the linear trends of each model's forecast removed, but the results with the linear trends remain almost similar.

Figure 1 shows the linear regression of wintertime SATs with respect to ART1, denoting the SAT averages over BKS, from the ERA-interim (OBS), MME, and the individual model forecasts. Previous observational studies have suggested that positive ART1 was accompanied by positive and negative pressure anomalies downstream, which led to a strengthening of the Siberian High and Eurasian cooling (Honda *et al* 2009, Mori *et al* 2014, Kug *et al* 2015). OBS in figure 1 clearly shows the Eurasian cooling. Most models simulate the concurrence of BKS warming and Eastern Continental Eurasia (ECE: 35–60°N, 80–125°E) cooling to some extent (or BKS cooling and ECE warming as well). Hereafter, we describe the Arctic-midlatitude relationship mainly with a perspective of Arctic warming vs. midlatitude cooling for brevity. The pattern correlation coefficients (PCC) between OBS and the individual model are about 0.64–0.94. In some models (HMC, CMAM, L85GL4, and POAMA), the negative SAT that regressed in ART1 over the Eurasian region was barely apparent. Still, in many of the



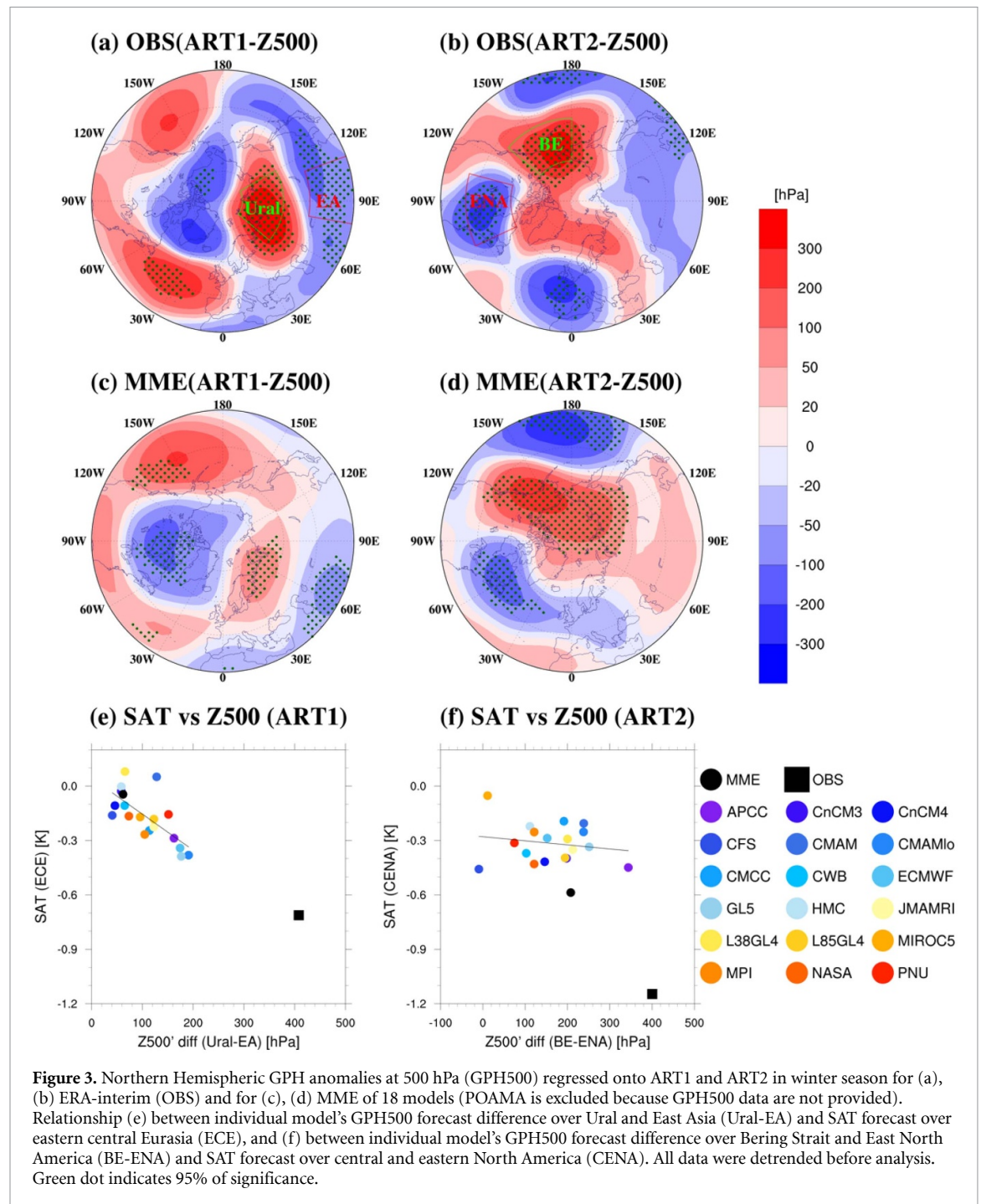
other models (CMCM, CMCC, ECMWF, JMAMRI, MPI, NASA), the negative correlation was strong even though the magnitude was lower than found in OBS. MME seemingly captures the overall pattern of ART1-related teleconnection (PCC is 0.91) despite some inconsistency compared to OBS. Significant warm anomalies extend more to Siberia, and cold anomalies in lower-latitude are less significant. In the case of ART2, similarly, previous studies suggested that anomalous warming over the ECS was followed by anticyclonic systems in the Bering Sea and cyclonic circulation anomalies over western North America, which led to cooling over inland North

America (Kug *et al* 2015, Yu *et al* 2018). OBS in figure 2 well represents cooling over North America. Most models simulated a negative correlation with the SATs over central and eastern Northern America (CENA: lon-lat information) (Biancamaria *et al* 2011) except HMC, L85GL4, and MIROC5. The PCCs between OBS and individual models (0.47–0.88) were slightly lower than those in ART1, but the MMEs simulated the overall relationship between the ECS-CENA realistically, especially in the North Pacific–North America region. However, the negative correlation over the Eurasian continent found in OBS, even though it is not significant, is not captured by MME.

Figures 3(a)–(d) represent large-scale atmospheric circulation changes, geopotential height anomalies at 500 hPa (GPH500), linked to Arctic temperature (i.e. ART1 and ART2). Previous studies suggested that large-scale atmospheric circulation patterns connect Arctic warming and midlatitude cooling (Kim *et al* 2014, Mori *et al* 2014, Kug *et al* 2015). Over the Eurasian sector, positive pressure anomalies centered over the Ural Mountains and negative pressure anomalies centered over Mongolia develop in association with the BKS warming (Mori *et al* 2014, Kug *et al* 2015). The subsequent strengthening of the Siberian High leads to surface cooling over mid-latitude East Asia (Ye *et al* 2018). Over the North Pacific to North America sector, similarly, positive pressure anomalies centered over the Bering Strait and negative anomalies centered over the Hudson Bay develop in association with the ECS warming. Resulting northerly winds lead to cooling over eastern North America. These characteristics are found clearly in ERA-interim (OBS; figures 3(a) and (b)). Models' capability of simulating those atmospheric circulation patterns is represented in figures 3(c) and (d) (MME) and supplementary figures S5–S6 (available online at stacks.iop.org/ERL/15/094045/mmedia) (individual models). Models (MME) seemingly capture the overall features, but there is a considerable discrepancy compared to OBS. For the BKS warming (ART1), the positive pressure anomalies over western Russia is much weaker than OBS, and the negative pressure anomalies centered over Mongolia is much weaker and shifted westward slightly. There are considerable differences in the individual models' patterns. Overall, six models (CMAMlo, CMCC, ECMWF, JMAMRI, L85GL4, MIROC5, and MPI) simulate the significant high- and low-pressure anomalies associated with BKS warming (ART1), and most of them capture the significant cooling over midlatitude Eurasia. It seems that models have a slightly better capability in simulating the atmospheric circulation anomalies related to ART2 compared with those associated with ART1. For the ECS warming (ART2), anomalous high-pressure center over the Bering Strait further extends southeastward, and anomalous low-pressure center over eastern North America shifts eastward slightly compared to OBS. CFS and GloSea5 do not represent the significant positive center over the Bering Strait. CWB, L38GL4, and MIROC5 do not show negative anomalies over eastern North America, and the cooling responses are weaker than OBS or almost vanished. Figures 3(e) and (f) compare the strength of the pressure pattern (GPH500) difference between the anomalous high- and low-pressure centers with midlatitude temperature responses in different models, MME, and OBS. It can be seen that models better capture the atmospheric circulation patterns associated with Arctic temperature tend to simulate midlatitude cooling

closer to OBS. Overall, those results emphasize that the accurate simulation of atmospheric circulation patterns in response to Arctic warming is essential to simulate the midlatitude responses realistically.

Based on these results, we see that the many operational forecast models have the capability to simulate the Arctic-midlatitude teleconnection found in observational data. But this does not necessarily guarantee a positive contribution to SAT forecast skill in the midlatitudes (cf figures 4 and 7). The forecast skill of the Arctic temperature is much contributed by various internal and external factors such as the initialization of atmosphere-ocean-sea ice. And the Arctic-midlatitude teleconnection is sustained by large-scale atmospheric circulation linked to the Arctic temperature variation, regardless of its accuracy. Therefore the Arctic temperature forecast skill is not necessarily consistent with the model's capability to simulate the teleconnection pattern. In other words, it is possible that some models fail to predict the Arctic temperature but can simulate the teleconnection pattern realistically, or vice versa. Figure 4 compares the forecast skill (ACC between the forecasted and observed values) of ART in the 19 models. The skill varied greatly between models, ranging from 0.07 to 0.63. For ART1, two models (NASA and GloSea5) and MMEs showed relatively good skills (ACC > 0.5), but most models resulted in a lower than 0.5 ACC. For ART2, the models tended to show worse skills than in ART1. 17 models showed very limited skills (ACC < 0.3). This was not of high quality as compared to that found in other parts of the globe (average ACC over NH of 0.46). Over the tropical eastern Pacific region, especially, all models show high skills (average ACC of 0.91), which is an important source for seasonal forecasts for the extratropics based on the well-known tropic-extratropics teleconnection. The lower skills in ART2 compared to ART1 are perhaps because the ECS region is mostly covered in ice in winter, so the atmospheric dynamics dominate the SAT variability. Notably, ice cover variability in the ECS region has greatly increased recently with several cold spells occurring concurrently in North America (Tachibana *et al* 2019). However, the analysis period of this study (1979–2014) does not cover this variability. One important result to note is that the models with interactive sea ice processes tend to show better ART forecast skills than those with prescribed sea ice conditions, especially in ART1. This indicates that realistic feedback between sea ice and ocean in the Arctic is essential for accurate simulations of the Arctic climate. However, climate models still have considerable uncertainty in simulated sea ice and reliable observations on which to base the models is limited (Vihma 2014, Gerland *et al* 2019). Overall, the results suggested that the low forecast skill of the Arctic SAT compromises the ability to predict midlatitude SAT. In other words, there is a potential to improve



the midlatitude forecast skill with an accurate Arctic SAT forecast.

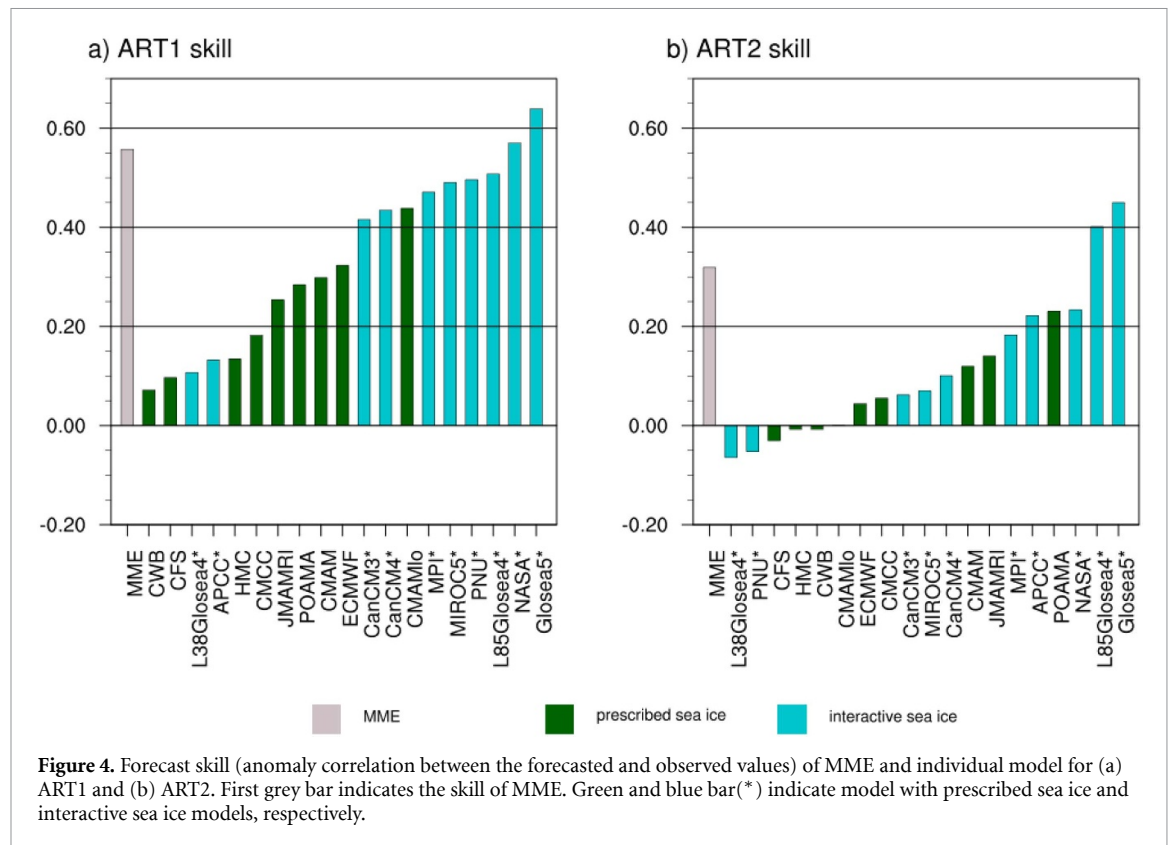
3.2. Contribution of Arctic-midlatitude teleconnection to forecast skills

Next, we examined the possible contribution of the Arctic-midlatitude teleconnection to SAT forecast skill. As shown in the previous section, the forecast models seem to have the potential to simulate spatial patterns of the Arctic-midlatitude teleconnection, but, as shown in figure 4, most of the models exhibit relatively poor forecast skills for the Arctic SAT itself and, thereby, the practical contribution to midlatitude forecast capabilities is

currently limited. What if the models could forecast the Arctic temperature accurately? We tested this assumption by correcting individual model's forecasts with perfect (observed) ARTs while keeping the original Arctic-midlatitude teleconnection for each individual model (i.e. regression obtained from the hindcast). This was done using the following simple statistics (1).

$$\text{SAT}_{\text{cor}} = \text{SAT}_f + (\text{ART}_o - \text{ART}_f) \text{Reg}(\text{ART}_h, \text{SAT}_h) \quad (1)$$

Here, SAT_{cor} represents the SAT forecast corrected by a perfect ART and a model's original



teleconnection patterns. Here, f , o , and h indicate forecast, observation, and hindcast, respectively. **Reg** indicates the linear regression. The difference in results between the corrected and original forecasts represents the potential forecast skill improvement that can be obtained in current models with perfect ART in regards to the Arctic-midlatitude teleconnection.

Figure 5 shows forecast skill changes in the Northern Hemisphere using the above statistical corrections. For clarity, the results for MME are shown here (each individual model's SAT forecast skill and its changes due to ART correction are in the supplementary figures S1–S3). The average of individual models' skills did not differ much from this. Without any corrections, the models (shown in figure 5(a)) get high skills in the Alaska-Canada region of North America, Greenland, and the southern part (30°N) of the Eurasian continent, mainly in China and Central Asia. In most parts of Europe and Russia, the prediction skill are relatively low and statistically insignificant. When the ART1 index (SAT over the BKS) is corrected, the forecast skill improves significantly (ACC 0.1 to 0.2) over the midlatitudes of the Eurasian continent. Notably, the skill improvements in the sub-Arctic part of the BKS region, where the SAT was directly modified by the corrections, and around Mongolia and central Russia, is remarkable (figure 5(c)). The regions where the results improve roughly match the two centers of the ART1 teleconnection in figure 1 (BKS and ECE). This clearly shows that the seasonal forecast skills

in the midlatitudes, specifically when utilizing the Arctic-midlatitude teleconnection, can be improved considerably only if the ART1 is forecasted realistically. The possible skill improvements from ART2 (figure 5(d)) is also evident in the area near the Bering Sea and North America, where the two centers of the ART2-CENA teleconnection are located, as seen in figure 2. In the original forecast, there are no statistically significant results in most of the United States, but the ART2 correction provides significant results over the eastern part of the United States and most regions of Canada. Since the overall forecast skill of ART2 in the current models was relatively lower than that of ART1, the potential skill improvement from a perfected ART2 was larger than that from ART1. However, an ART2 correction seemed to have a negative effect on northern Eurasia. This is because the models especially misrepresent the ART2-teleconnection in this region, as seen in figure 2. ERA-interim (OBS) shows an overall negative correlation in northern Eurasia, while most models (MMEs) simulate a positive correlation there. However, the negative correlation is not statistically significant, so it could just result from large internal variability, not from a physical teleconnection. We additionally examined the changes in root mean squared error of the forecasts due to the ART correction (supplementary figure S4). In consistent with the ACC, the forecast error reduces over the focused mid-latitude regions, again confirming the potential improvement of forecast skill from the Arctic-midlatitude teleconnection.

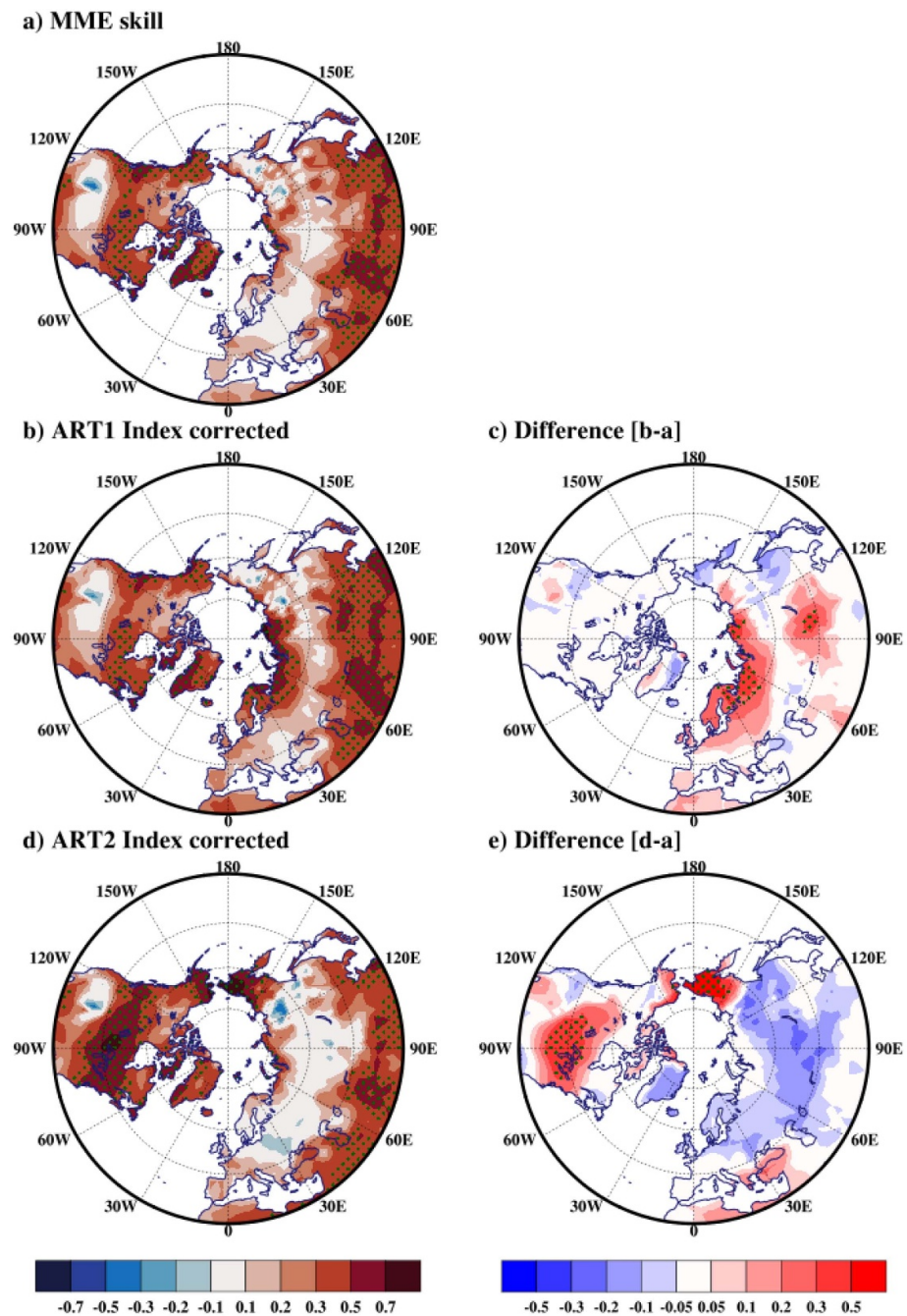
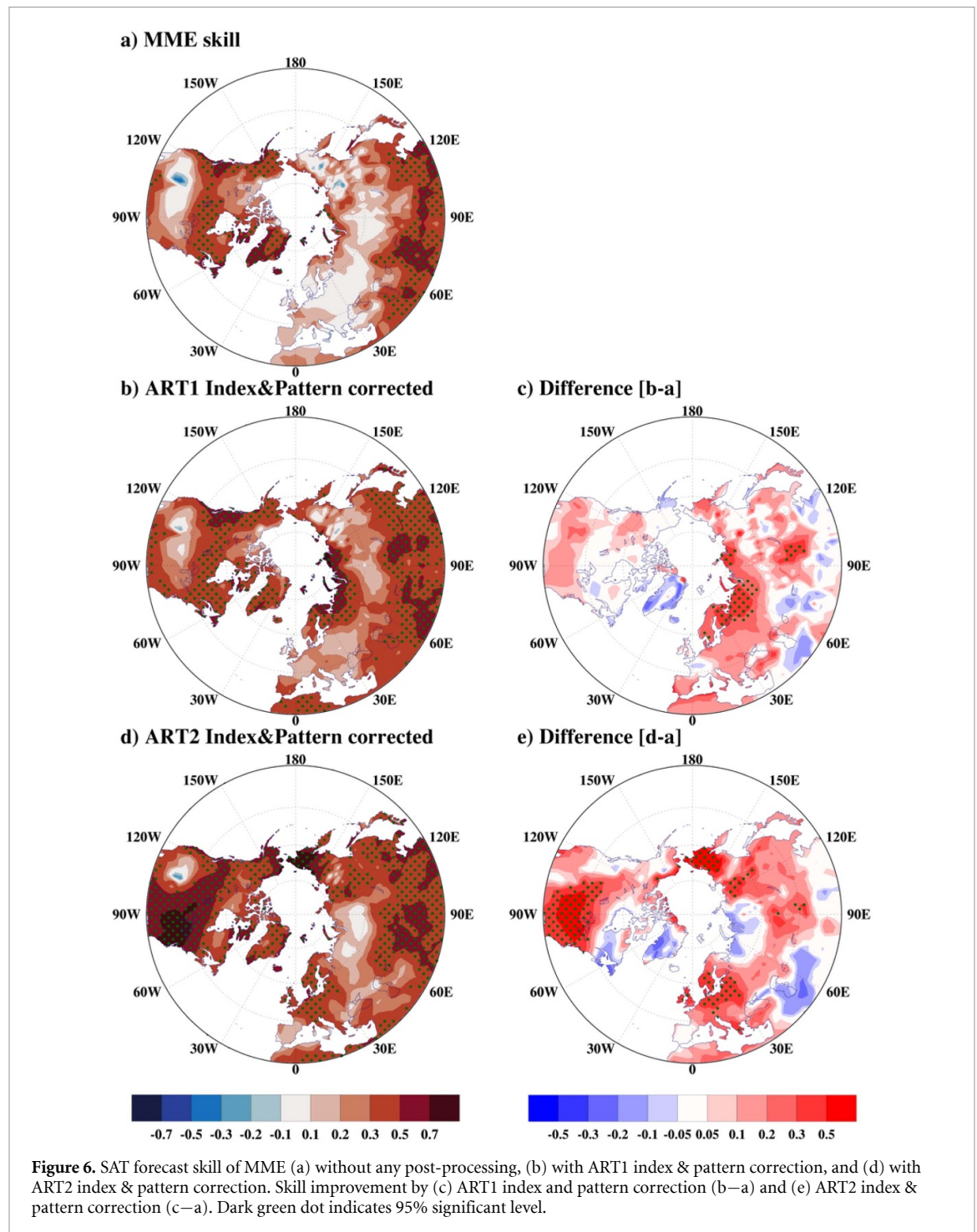


Figure 5. SAT forecast skill of MME (a) without any post-processing, (b) with ART1 index correction, and (d) with ART2 index correction. Skill change by (c) ART1 index correction (b–a) and (e) ART2 index correction (d–a). Dark green dot indicates 95% significant level.

Since the statistical correction was done for quantifying the potential impact on forecast skills, the teleconnection pattern was estimated with data for the entire analysis period. However, one can raise a question about reliability of our approach, particularly the possibility that statistical correction term could change in time. For observations, Kug *et al* (2015) showed that the ARTs-teleconnection patterns remained similar when they calculated the regression with temperature data available for a more extended period (1890–2014). We also have examined the change with ERA-interim, and found that the overall pattern remained largely unchanged within

the analysis period (supplementary figure S7). For models' forecast, we have calculated the possible skill change by the correction as in figures 5(c) and (e) but for the different three decades (the 1980s, 1990s, and 2000s) separately (details in supplementary figure S8). Still, the general patterns of the impact of Arctic-midlatitude teleconnection on the forecast skill, especially for East Asia and eastern North America, remained quite similar, at least, for our analysis period.

In addition, we tested more idealized cases. What if the models simulated the spatial patterns of the Arctic-midlatitude teleconnection perfectly (as OBS

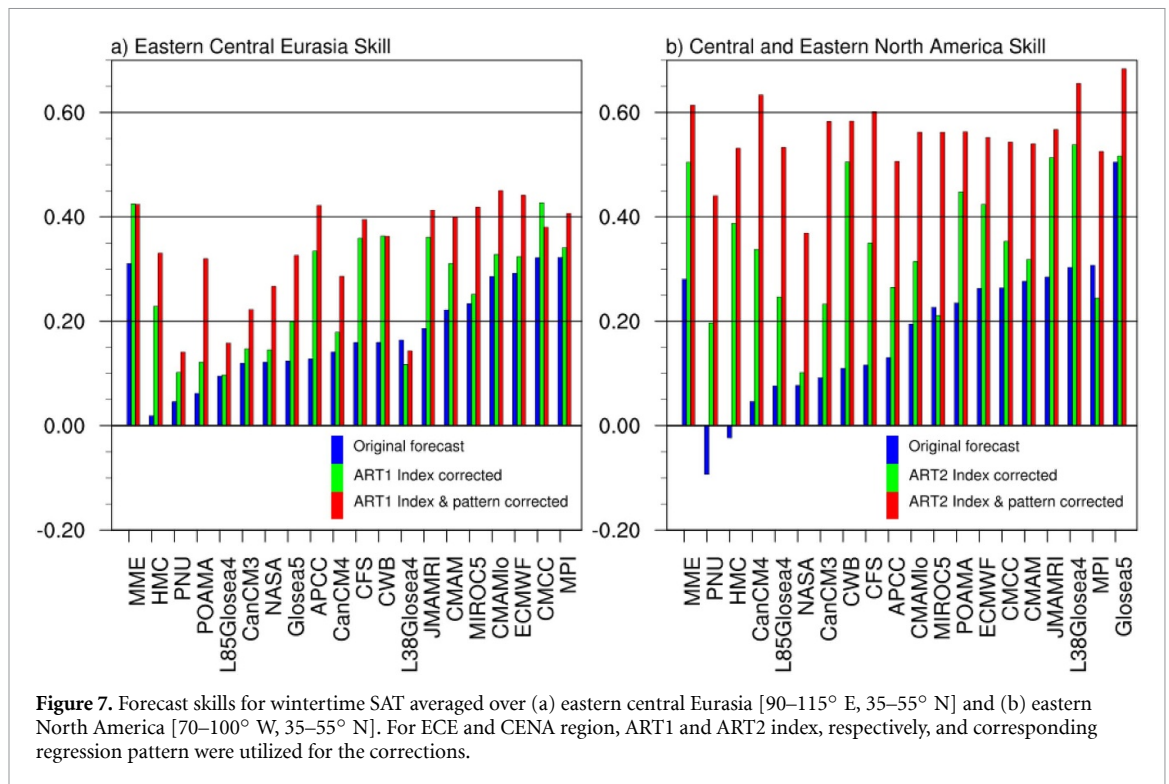


in figures 1 and 2) as well as the Arctic temperature? As mentioned in section 3.1, models seemed to capture the overall inverse correlation between the Arctic and the midlatitudes (figures 1 and 2) but still showed considerable discrepancies when compared with observational data. MME can capture the most of main features of the teleconnection, but the detailed spatial pattern was different from observational data, and the magnitude of the negative correlation between the Arctic regions and the midlatitudes was much weaker than observed. With another simple statistical adjustment to equation (1), we corrected the models' forecasts to use observed (perfect) spatial

patterns of the Arctic-midlatitude teleconnection as well as a perfect ART, resulting in equation (2).

$$\text{SAT}_{cor'} = \text{SAT}_f - \text{ART}_f \text{Reg}(\text{ART}_h, \text{SAT}_h) + \text{ART}_o \text{Reg}(\text{ART}_o, \text{SAT}_o) \quad (2)$$

Equation (2) simply replaces the models' spatial representation of the Arctic-midlatitude teleconnection from a forecast to observational data. It is a highly idealized assumption but suggests what the upper limit of the forecast potential could be with regards to the Arctic-midlatitude teleconnection. Figure 6 shows the improved results from the



corrections. For ART1, the forecasting improvements were found across the Eurasian continent, over a wide area (most of extratropical Eurasia) and by large amounts. There was an improvement in results in the US as well, though it was not statistically significant. For ART2, the forecast skill improvement over North America was conspicuous. The difference in results was statistically significant over most parts of the United States. Given the correction of the teleconnection in ART2, the forecasting improvement was also notable over Eurasia. This is because the discrepancy between the Eurasian continent in OBS and MME, shown in figure 2, was corrected.

Figure 7 summarizes the potential improvement of SAT forecast skill over the focused midlatitude regions—ECE and CENA due to the Arctic-midlatitude teleconnections. This result clearly highlights that the realistic simulation of Arctic-teleconnection patterns and Arctic temperatures can significantly improve forecast skills in the midlatitudes.

4. Conclusion and discussion

In the present study, the impacts of the Arctic-midlatitude teleconnection on winter climate forecasts on the midlatitudes were assessed by analyzing extensive archives of seasonal forecast datasets from 19 operational climate models. The results reveal that most climate models were capable of simulating the Arctic-midlatitude teleconnection patterns of both the eastern Eurasian and the North American regions. However, we also found that this simulated Arctic-midlatitude teleconnection can be

still limited due to poor predictability of Arctic temperature itself. Idealized analysis assuming a perfect forecast of Arctic temperature shows that considerable forecasting improvement can be achieved, and further improvements are possible with accurate simulations of the Arctic and its teleconnection patterns.

On the other hand, we should interpret the results with caution for a few reasons. First, the potential forecast skills can be converted to actual skills only if the teleconnection between the Arctic and the midlatitudes exists. Despite evidence found in observational data, the causal relationship between the Arctic and the extratropics is still debated in the literature and dependent on the modelling system (Cohen *et al* 2020). Second, we applied a simple linear regression to the corrected models' forecasts of ARTs and teleconnection pattern, though the Arctic and midlatitude teleconnection are strongly affected by non-linear processes which were not considered in the present analysis. Third, the present study hypothesized the Arctic-midlatitude teleconnection pattern to be stable with time. Even though its overall pattern remained largely similar within the analysis period (shown in supplementary figures S7 and S8), there have been detectable changes in its strength and spatial pattern with time. For instance, East Asian cooling response associated with BKS warming weakened notably in the 1990s. Perhaps, the continuing loss of Arctic sea ice change the strength and pattern of Arctic warming significantly in the near future, which definitely leads to subsequent changes in Arctic-midlatitude teleconnection. Fourth, we tested what would happen if we could make perfect forecasts of Arctic temperature, but that is not an

easy task to achieve in the real world. Still, observational data from the Arctic are insufficient, resulting in a lack of understanding and accuracy in model simulations of complex interactions between the atmosphere, ocean, and sea-ice (Vihma 2014, Gerland et al 2019). Recent efforts for Polar observation projects like YOPP (Year Of Polar Prediction; Jung et al 2016) and MOSAC (The Multidisciplinary drifting Observatory for the Study of Arctic Climate; mosaic-expedition.org) expedition have improved the observation data situation over the polar region considerably. In addition to observational systems, further improvement of climate modelling system, and proper initialization methods are required.

In this study, we focused mainly on temperature and its predictabilities, but there are multiple factors including other variables like atmospheric pressure, sea surface temperature, wind, as well as individual model's characteristics and bias could play a role to play in the Arctic-midlatitude teleconnection. This will be the focus of our future studies. Despite many limitations, this study suggests that the Arctic-midlatitude teleconnection can offer a new additional source of seasonal forecast capabilities over the midlatitudes.

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Data availability

The data that support the findings of this study are openly available at <http://www.wcrp-climate.org/wgsip-chfp/chfp-data-archive> and <http://adss.apcc21.org>

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