Subseasonal Forecast Skill over the Northern Polar Region in Boreal Winter

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ABSTRACT

Pentad (5-day averaged) forecast skill over the Arctic region in boreal winter is evaluated for the subseasonal to seasonal prediction (S2S) systems from three operational centers: the European Centre for Medium-Range Weather Forecasts (ECMWF), the U.S. National Centers for Environmental Prediction (NCEP), and Environment and Climate Change Canada (ECCC). The results indicate that for a lead time longer than about 10 days the forecast skill of 2-m air temperature and 500-hPa geopotential height in the Arctic area is low compared to the tropical and midlatitude regions. The three S2S systems have comparable forecast skill in the northern polar region. Relatively high skill is observed in the Arctic sector north of the Bering Strait in pentads 4–6. Possible sources of S2S predictability in the polar region are explored. The polar forecast skill is found to be dependent on the phase of the Arctic Oscillation (AO) in the initial condition; that is, forecasts initialized with the negative AO are more skillful than those starting from the positive AO. This is likely due to the influence of the stratospheric polar vortex. The tropical MJO is found to also influence the prediction skill in the polar region. Forecasts starting from MJO phases 6–7, which correspond to suppressed convection in the equatorial eastern Indian Ocean and enhanced convection in the tropical western Pacific, tend to be more skillful than those initialized from other MJO phases. To improve the polar prediction on the subseasonal time scale, it is important to have a well-represented stratosphere and tropical MJO and their associated teleconnections in the model.

1. Introduction

Increasing needs and interests in polar predictions have become evident in recent years (e.g., [Jung et al. 2016](#)). The demand for reliable weather prediction in the northern polar region is associated with increased economic and transportation activities (e.g., [Smith and Stephenson 2013](#)). The interest in polar climate variability and prediction comes partly from concerns about the accelerated warming (i.e., Arctic amplification) in the polar regions and decline of sea ice coverage in recent years (e.g., [Holland and Bitz 2003](#)). There is also potential influence of Arctic amplification on midlatitude circulation and weather conditions (e.g., [Francis and Vavrus 2012](#); [Cohen et al. 2014](#); [Coumou et al. 2018](#)). Compared to the middle latitudes and the tropics, less is known about the atmospheric predictability in the polar region. Great challenges of making useful polar weather

predictions exist, due to the remoteness of the region, lack of in situ observations, and lack of understanding of sources of predictability.

Although global numerical weather forecasting systems have been in operation for several decades, there have only been a limited number of studies on their performance in the polar region. [Jung and Leutbecher \(2007\)](#) reported that the improvement in deterministic forecasts for the European Centre for Medium-Range Weather Forecasts (ECMWF) forecasting system in the Arctic from early 1980s to the mid-2000s follows closely that of the Northern Hemisphere as a whole. Using the THORPEX Interactive Grand Global Ensemble (TIGGE) dataset, [Bauer et al. \(2016\)](#) and [Jung and Matsueda \(2016\)](#) assessed the forecast skill of several operational medium-range ensemble prediction systems in the polar region. General improvement of forecast quality was found in the polar region, which shows similar trends to those of the lower latitudes. Forecast skill in the Arctic appears comparable to that of the Northern Hemisphere midlatitudes, but the differences in forecast quality among different forecasting systems are larger in the polar region. These studies are for

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numerical weather predictions on short to medium ranges with a lead time up to two weeks.

Recently we have seen an increase of interest in subseasonal to seasonal (S2S) predictions, which have a lead time from two weeks to a season. S2S prediction has obvious potential societal and economic benefits. The importance of advancing subseasonal prediction has been stressed in several studies (e.g., [Brunet et al. 2010](#); [Shapiro et al. 2010](#); [National Academies of Sciences, Engineering, and Medicine 2016](#)). Several international collaborative S2S projects have been established to address this issue. For example, the international S2S project of the World Weather Research Programme (WWRP)/World Climate Research Programme (WCRP) of the World Meteorological Organization (WMO) has been established to improve coordination among operational centers in order to improve S2S forecast skill and applications by filling the gap between medium-range and seasonal forecasting ([Vitart et al. 2015](#)). The Subseasonal Experiment (SubX) is a NOAA/Climate Testbed project, which is a multimodel S2S prediction effort including several North American models ([Pegion et al. 2019](#)). Most of the WMO Global Production Centers have started producing operational subseasonal forecasts ([Vitart et al. 2017](#)). However, how the global numerical models perform in the polar region on the S2S time scale is unclear.

One major circulation pattern in the extratropical Northern Hemisphere that is relevant to polar prediction is the northern annular mode (NAM) or the Arctic Oscillation (AO; e.g., [Thompson and Wallace 1998, 2000](#)), which is characterized by an out-of-phase change in sea level pressure between the Arctic and the midlatitudes. The North Atlantic Oscillation (NAO; e.g., [Hurrell et al. 2003](#)), an important mode of variability influencing the weather and climate in eastern North America and Europe, is a regional expression of the NAM/AO in the North Atlantic sector. Comparing to other extratropical modes of variability in the troposphere, a unique behavior of the NAM/AO is its coupling with the stratospheric polar vortex in the boreal winter season. The stratospheric polar vortex can be represented by an area of low pressure over the Arctic with a zonally symmetric structure similar to the NAM/AO. The stratospheric NAM/AO anomaly propagates downward, which can influence the tropospheric AO (e.g., [Baldwin and Dunkerton 1999, 2001](#); [Kidston et al. 2015](#)). The AO was found to influence the Arctic sea ice and weather condition (e.g., [Wang and Ikeda 2000](#)). Several recent studies have investigated the influence of AO/NAO on the predictability on the S2S time scale. For example, [Ferranti et al. \(2015\)](#) found that the subseasonal forecast is more skillful in the North Atlantic–

European sector for the negative NAO weather regime than for the positive NAO. Similar results were reported in [Matsueda and Palmer \(2018\)](#). However, what causes this difference in forecast skill between positive and negative AO/NAO is not understood. How the AO/NAO influences the predictability in the Arctic region is also unclear.

The Madden–Julian oscillation (MJO) is the dominant mode of variability in the tropics on the subseasonal time scale, which is characterized by a large-scale 30–50-day tropical wave coupled with convection propagating eastward along the equator ([Madden and Julian 1971](#)). The tropical large-scale convection anomaly associated with the MJO excites extratropical Rossby waves that propagate across a long distance in the extratropics, significantly influencing the global weather and climate. The MJO-related teleconnection provides an important source of predictability on the subseasonal time scale (e.g., [Waliser et al. 2003](#); [Lin and Brunet 2009](#); [Lin et al. 2010a,b](#)). The MJO was observed to influence the AO/NAO (e.g., [Zhou and Miller 2005](#); [Lin et al. 2009](#)). The AO/NAO tends to have a lagged connection with the MJO, with positive (negative) NAO occurring about two weeks after the MJO convection is enhanced in the equatorial Indian Ocean (western Pacific) (e.g., [Lin et al. 2009](#)). The MJO was also found to influence the polar temperature (e.g., [Yoo et al. 2011](#)), and sea ice (e.g., [Henderson et al. 2014](#)). Furthermore, the MJO can affect the Northern Hemisphere stratospheric polar vortex through vertically propagating Rossby waves (e.g., [Garfinkel et al. 2012](#)), and the MJO influence on the NAO may go through a stratospheric pathway (e.g., [Jiang et al. 2017](#)). It would be interesting to see how the MJO influences the polar prediction skill on the subseasonal time scale.

The objective of this study is to assess the quality of state-of-the-art global prediction systems on the S2S time scale in the northern polar region. The dependence of the forecast skill on the quality of verification data will be partly addressed using two different reanalysis datasets. The forecast skill in the Arctic region will be compared to that in the middle latitudes and the tropics. We will then explore the sources of S2S predictability in the polar region. Specifically, the roles played by the AO/NAO and the MJO will be discussed.

The paper is organized as follows. [Section 2](#) describes the data and analysis method. The forecast skills of surface air temperature and 500-hPa geopotential height in the northern polar region are presented in [section 3](#). [Section 4](#) discusses the influence of the NAM/AO on the polar S2S prediction. The possible connection with the stratosphere is also analyzed. In [section 5](#), the impact of

the MJO on the polar prediction is assessed. A summary and discussion are given in [section 6](#).

2. Data and method

To evaluate the forecast skill in the polar region, we use the hindcast data of subseasonal prediction systems from three operational centers: ECMWF, the U.S. National Centers for Environmental Prediction (NCEP), and Environment and Climate Change Canada (ECCC). The data analyzed here come from the Global Ensemble Prediction System (GEPS) 4.0 of ECCC, CY40R1 and CY41R1 of ECMWF, and CFSv2 of NCEP, which were in operation in 2015. Both the ECMWF and NCEP systems were running with air–sea coupled models and active sea ice, while the ECCC system is an atmospheric-only model and with specified persistent sea surface temperature (SST) and sea ice anomalies ([Vitart 2004](#); [Saha et al. 2014](#); [Lin et al. 2016](#)). The hindcast data are obtained from the S2S archive database ([Vitart et al. 2017](#)), covering the period of 12 years from 1999 to 2010, which is common to the three models. The selected hindcasts correspond to the weekly real-time forecasts initialized at 0000 UTC every Thursday in the months of January, February, March, November, and December 2015 to represent the extended winter. Each winter has 22 forecasts, with a total of 264 forecasts during the 12 hindcast years. To facilitate a comparison of forecast skill, for each model four members are used to construct ensemble means. For the ECMWF reforecast, the first four perturbed members out of 11 ensemble members are used. Although all the S2S systems produce ensembles of forecasts, only the deterministic aspect of the forecast skill is considered, as the ensemble size for the hindcast data analyzed here is small.

In the polar region, due to a limited number of observations the quality of atmospheric analysis is not as good as the midlatitude and tropical regions. To address the uncertainty of the observations, two reanalysis datasets are used as the reference of verification. These are the daily data of the ECMWF interim reanalysis (ERA-Interim; [Dee et al. 2011](#)), and the daily values of the NCEP–NCAR (National Center for Atmospheric Research) global reanalysis ([Kalnay et al. 1996](#)). The variables used include 2-m air temperature (T2m) and 500-hPa geopotential height (Z500). The analysis is performed on the NCEP–NCAR reanalysis grid of $2.5^\circ \times 2.5^\circ$. The ERA-interim data are interpolated to the $2.5^\circ \times 2.5^\circ$ grid from the original $0.75^\circ \times 0.75^\circ$ grid.

To focus on the subseasonal time scale, the forecast values are averaged for consecutive five days (pentad), with pentad 1 as days 1–5, pentad 2 as days 6–10, and so

on. For each forecast date, the four-member ensemble mean is first calculated. Then pentad averages are made. Thus, the forecast has lead times from 1 to 6 pentads. The climatology of each pentad is the 12-yr average of forecasts for the same pentad from 1999 to 2010. Therefore, it is the average of 240 values ($12 \text{ years} \times 4 \text{ members} \times 5 \text{ days}$), which is likely a good representation of the model climatology of that forecast pentad. For the observations, because of only one ensemble member, the climatology for each verification pentad is the average of 60 days. The forecast pentad anomaly is obtained by removing the model climatology of the same pentad with the same lead time. Observed pentad data are also calculated for the corresponding target periods from the ERA-Interim and NCEP–NCAR reanalysis data for verification. As will be seen in the following sections, in most cases the skill results with the two reanalysis datasets are similar. Therefore, in the following discussions the illustrated verification results are those using the ERA-Interim reanalysis, unless mentioned explicitly.

The daily AO index is obtained from the Climate Prediction Center (CPC) website (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html). It was calculated as projection of the daily (0000 UTC) 1000-hPa geopotential height anomalies poleward of 20°N onto the first mode of the empirical orthogonal function (EOF) of the monthly mean 1000-hPa geopotential height anomalies. To distinguish this AO index from those of the other levels, we refer to it as AO₁₀₀₀. Another index (ZP500) describing the AO at 500 hPa is defined as the 500-hPa geopotential height (Z500) anomaly averaged over the polar cap ($>60^\circ\text{N}$), and then normalized. Using the daily ERA-Interim Z500 from 1979 to 2014, the Z500 anomaly is calculated by removing the daily annual cycle, which is the annual mean plus the first three harmonics of the 35-yr daily climatology. Note that ZP500 is anticorrelated with the AO. To represent the AO/NAM and polar vortex in the stratosphere, ZP50 is calculated in a similar way as ZP500 except that this time the 50-hPa geopotential height (Z50) anomaly over the polar cap ($>60^\circ\text{N}$) is used.

The MJO amplitude and phase are defined by the real-time multivariate MJO indices (RMM; [Wheeler and Hendon 2004](#)), which are obtained as the principal components of the two leading modes of the EOF analysis of the combined fields of 15°S – 15°N meridionally averaged OLR and zonal winds at 850 and 200 hPa. The daily RMM index values are downloaded from the Australian Bureau of Meteorology website (<http://www.bom.gov.au/climate/mjo>).

FIG. 1. Correlation skill of three-model ensemble averaged T2m (a) against ERA-Interim and (b) against NCEP-NCAR.

3. Forecast skill in the northern polar region

a. 2-m temperature

We first compare the polar forecast skill of T2m with that in the midlatitudes and the tropics. With the 264 forecasts, temporal correlation is calculated between the three-model ensemble mean forecast and the observed pentad T2m anomaly at each grid point to get the multimodel ensemble mean forecast skill. Shown in Fig. 1 is the correlation skill averaged over the northern polar ($>60^{\circ}\text{N}$), midlatitude ($30^{\circ}\text{--}60^{\circ}\text{N}$), and tropical ($30^{\circ}\text{S}\text{--}30^{\circ}\text{N}$) regions as a function of lead time. Figure 1a is verified against the ERA-Interim reanalysis data, while Fig. 1b is against the NCEP-NCAR reanalysis. As can be seen, the skill is in general independent of the verification data. The forecast skill in the midlatitudes is the highest for the short range up to two pentads, reflecting the model's ability in forecasting the midlatitude synoptic weather events that are likely related to the baroclinic instability dynamics. On the other hand, the short-range forecast skill in the tropics is the lowest, which is likely caused by the small-scale nature of tropical convection. With the increase of the forecast lead time, the skill drops for all regions, although the decrease of skill is slower for the tropics than for the midlatitude and the polar areas. On the S2S time scale beyond two pentads, it is clear that the tropics has the best skill, which is possibly associated with the slowly varying SST and some large-scale low-frequency oscillations such as the MJO. The S2S forecast skill in the northern polar region is the lowest among the three regions. In pentad 6, for example, the correlation skill in the middle latitudes is about half of that in the tropics, and the polar skill is about one-third of that in the

tropics. The low S2S forecast skill in the polar area indicates that there is lack of predictability in this region and it is especially challenging to make polar weather predictions beyond about two weeks.

Now we compare the polar prediction skill among the three operational S2S forecast systems. Shown in Figs. 2a and 2b are the T2m correlation skill averaged over the northern polar ($>60^{\circ}\text{N}$) area for the three systems verified against the ERA-Interim and NCEP-NCAR reanalyses, respectively. The skill in the short range does seem to depend on the verification data. The ECMWF system, which is initialized with the ERA-Interim reanalysis atmospheric condition, has the best skill when verified against the ERA-Interim reanalysis (Fig. 2a), whereas the NCEP system, which uses the NCEP Climate Forecast System Reanalysis as its initial condition, has the highest skill when verified against the NCEP-NCAR reanalysis (Fig. 2b). ECCC does not have its own reanalysis system to initialize the hindcast. Their hindcast initial condition is generated by perturbing the ERA-Interim reanalysis, which came from a model different from the ECCC forecast model. As a result, the ECCC short-range forecast skill is not as good as the ECMWF system but is better than the NCEP system when verified against the ERA-Interim reanalysis (Fig. 2a). On the S2S time scale (pentads 4–6), however, the three systems in general have a comparable forecast skill in the northern polar region. The S2S forecast skill is low and appears less dependent on the verification dataset.

To better understand the dependence of forecast skill at lead times of pentads 1–2 on the verification data as shown in Fig. 2, the ERA-Interim and NCEP-NCAR reanalysis data are compared in the polar region.

FIG. 2. T2m skill averaged over the northern polar region (>60°N) (a) against ERA-Interim and (b) against NCEP-NCAR.

Figure 3a shows the difference of winter mean T2m between the ERA-Interim and NCEP-NCAR reanalyses. As can be seen, on average in winter season, ERA-Interim has a warmer T2m than the NCEP-NCAR reanalysis in the Arctic, with a maximum difference over 4°C. Anomaly correlation of pentad T2m is also calculated between these two reanalysis datasets, which is illustrated in Fig. 3b. The correlation is less than 0.9 in most of the polar regions, indicating that the agreement between these two reanalysis datasets is not

as good as in the middle latitudes. The minimum correlations are found mainly in two regions, one located to the north of Canada and Greenland and the other to the north of Russia. The inconsistency between the reanalysis datasets should be taken into account in studies on polar atmospheric variability and predictions.

Figure 4 illustrates the spatial distribution of T2m correlation skill of pentads 4–6 in the northern polar region for the three operational S2S systems. The verification is against the ERA-Interim reanalysis, but the

FIG. 3. (a) Difference of winter (November–March) mean T2m between ERA-Interim and NCEP-NCAR reanalysis. Contour interval is 2°C. Contours with negative values are dashed. The zero contour is omitted. (b) Anomaly correlation of pentad T2m between ERA-Interim and NCEP-NCAR reanalysis. Contour interval is 0.1. The map limit is the 60°N circle.

FIG. 4. Correlation skill of T2m at pentads 4–6 for (a)–(c) ECCC, (d)–(f) ECMWF, and (g)–(i) NCEP. Areas in yellow indicate a significance level of 0.05; orange indicates a significance level of 0.01. The verification is against the ERA-Interim reanalysis. Contour interval is 0.1. The map limit is the 60°N circle.

results are very similar to those obtained with the NCEP–NCAR reanalysis (not shown). The orange color shaded areas are for those with correlation skill that is statistically significant at the 0.01 level according to the Student's t test. The skill drops with lead time, but even

at pentad 6 there is a fairly large area in the polar region with significant forecast skill. Although the correlation skill of 0.3 to 0.4 for pentads 5 and 6 is only modest, it indicates that there is potential to obtain useful forecast information in the polar region. The S2S forecast skill

FIG. 5. Correlation skill of three-model ensemble mean Z500 (orange and brown bars) and T2m (green and blue bars) (a) against ERA-Interim and (b) against NCEP-NCAR.

over the Arctic is located mainly in two areas, one over the sector north of the Bering Strait and the East Siberian Sea and the other centered near the Barents Sea. The skills in the ECCO and ECMWF systems are very similar in magnitude and distribution. The NCEP system has a similar distribution with the other two models, but the magnitude is slightly weaker over the East Siberian Sea. The common distribution of skill among the three S2S models suggests that there exists some predictability in the polar region, and the three models are able to capture the same signals and sources of skill. The forecast skill is better over the sea ice than over the land. This indicates that the boundary forcing of sea ice is likely contributing to the forecast skill on the S2S time scale.

b. 500-hPa geopotential height

The area averaged multimodel ensemble mean forecast skill for Z500 is presented in Fig. 5. Considering that Z500 does not well represent the tropical variability, only the skills in the middle latitudes and the polar region are compared. Similar as for T2m, the Z500 forecast skill of the medium range and the S2S time scale in the middle latitudes is higher than that in the polar area. This implies that the middle latitude atmospheric dynamics is contributing to the forecast skill, whereas there is limited source of predictability in the polar region. Another explanation for the difference of skill between the middle latitudes and the Arctic is that the source of skill possibly comes from the low-latitude tropical region. Figure 5 also compares the forecast skill of Z500 with that of T2m. In the short- to medium-range (pentad 1–3), the T2m forecast skill in both the middle latitudes and the Arctic region is lower than Z500. On the S2S

time scale (pentads 4–6), however, the T2m forecast skill is higher than Z500 in both the middle latitudes and the Arctic region. This is likely related to influences from the lower boundary (e.g., sea surface, land surface, and sea ice) that are contributing to the forecast skill of T2m more than to Z500 on the S2S time scale.

The Z500 skill averaged over the northern polar region for the three individual models is shown in Fig. 6a. In general, the three models have a comparable performance, although the ECMWF model has a slightly better skill in pentads 2–6 than the other two models.

The spatial distributions of Z500 correlation skill of pentads 4–6 in the northern polar region for the three operational S2S systems are presented in Fig. 7. The three S2S models behave quite similarly. The central polar region has a minimum of forecast skill. Relatively high skill appears in two regions, the East Siberian Sea and the area extending from southern Greenland to the Barents Sea. The skill drops significantly from pentad 4 to pentad 6.

4. Influence of the AO

On the S2S time scale the predictability is likely largely controlled by some large-scale atmospheric patterns that vary on frequencies lower than the synoptic-scale variability. Figure 8 shows the map of correlation between the pentad ZP500 and Z500 at every grid point. The pattern looks very similar to the negative phase of the AO. Therefore, the polar cap Z500 anomaly is a good representation of the AO or NAM, consistent with previous studies (e.g., Kushner 2010; Seviour et al. 2016). A positive (negative) ZP500 is associated with a negative (positive) AO. In fact, the

FIG. 6. (a) Z500 skill averaged over the northern polar region (60° – 90° N). (b) Skill of area-averaged Z500 for the polar cap (60° – 90° N). The verification is against the ERA-Interim reanalysis.

correlation between the daily ZP500 and the AO_1000 index is -0.72 (Table 1). The ZP500 forecast skill is presented in Fig. 6b, which represents the NAM/AO skill. Comparing with Fig. 6a, the AO forecast skill is better than the average of gridpoint Z500 skill over the polar region, especially for the long lead time. For example, at pentads 5 and 6, the ECCC and ECMWF models have a ZP500 forecast skill more than double of the area-averaged Z500 skill. This indicates that the large-scale AO/NAM pattern is more predictable than the general polar weather that includes small-scale features. The dynamical S2S forecast systems are in general more skillful than the persistence forecast (the brown bars in Fig. 6b), except for pentad 6 of NCEP. The ECMWF model performs better than the other two models for pentads 3–6. Both the ECCC and ECMWF models have a better AO/NAM forecast skill than NCEP in pentads 5–6.

To assess the influence of the AO/NAM on the polar forecast skill, T2m correlation skills averaged over the northern polar area ($>60^{\circ}$ N) are compared between two groups of forecasts, one group of forecasts initialized with positive ZP500 ($\text{ZP500} > +0.5$) and the other initialized with negative ZP500 ($\text{ZP500} < -0.5$). The +ZP500 forecast has 100 cases while the –ZP500 forecast has 69 cases. Shown in Fig. 9 is the difference of skill between the +ZP500 and –ZP500 forecasts. A positive difference value indicates that the +ZP500 forecast has a better skill than the –ZP500 forecast. As can be seen, the ECMWF and NCEP systems have significant positive difference values for pentads 4–6. The ECCC system also has positive difference values in pentads 5–6, although less statistically significant. This indicates that forecasts initialized with +ZP500

(or –AO) are more skillful than those starting from –ZP500 (or +AO) on the subseasonal time scale.

The above result is consistent with previous studies demonstrating that the prediction of negative AO/NAO is more skillful than positive AO/NAO (e.g., Ferranti et al. 2015). To shed light on the mechanism of this difference in skill between positive and negative AO, we show in Fig. 10a the autocorrelation of ZP500 in the 34 winters for dates of $\text{ZP500} > +0.5$ comparing to that of $\text{ZP500} < -0.5$. As can be seen, +ZP500 (–AO) is more persistent than –ZP500 (+AO). The difference is statistically significant for the lead times of pentads 4 and 5. A more persistent process is likely more predictable. This may explain why the negative AO is more predictable and the polar T2m prediction is more skillful when initialized with negative AO than the positive AO.

Then the question is why the negative AO (+ZP500) is more persistent than the positive AO (–ZP500). One possible reason is its link with the stratospheric polar vortex. Previous studies have shown that the NAM anomaly signal in the stratosphere can propagate downward to influence the troposphere AO as well and the surface weather condition (e.g., Baldwin and Dunkerton 1999). To represent the stratospheric polar vortex, the daily ZP50 index is calculated from the ERA-Interim reanalysis 50-hPa geopotential height data in the same way as ZP500. A large positive (negative) ZP50 corresponds to a strong negative (positive) NAM/AO and a weak (strong) stratospheric polar vortex. From Table 1, we can see that ZP50 has a skewness of 0.38, indicating that its distribution has a longer tail in the positive ZP50 (negative AO) side than the negative ZP50 (positive AO) side. Such a skewness in the stratospheric NAM/AO can be related to stratospheric

FIG. 7. As in Fig. 4, but for Z500.

sudden warming, which usually has a big amplitude and causes the NAM/AO to become negative rapidly. As explained in Baldwin and Dunkerton (1999), recovery of the polar vortex after a warming is largely a radiative process and it is relatively slow for such a negative AO to return to its normal state. Indeed, the positive ZP50 is

significantly more persistent than the negative ZP50, as shown in Fig. 10b, which compares the autocorrelation of ZP50 in the 34 winters for dates of ZP50 $> +0.5$ with that of ZP50 < -0.5 . The stratospheric polar vortex is coupled with the tropospheric AO, as is evidenced by the correlation between ZP50 and the ZP500 and AO

FIG. 8. Correlation between the pentad Z500 anomaly averaged in the polar cap ($>60^{\circ}\text{N}$) and the pentad Z500 anomaly at every grid point, from November to March from 1979/80 to 2013/14 (30 pentads each winter). Contour interval is 0.1. Contours with negative values are dashed. The zero contour is omitted. The orange shaded areas represent those with a correlation statistically significant at the 0.01 level.

indices in Table 1. Therefore, the influence from the stratospheric polar vortex is likely one of the explanations why predictions of the negative AO/NAO are more skillful than the positive AO/NAO, and the polar predictions initialized from negative AO/NAO have a better skill than those starting from positive AO/NAO.

5. Influence of the MJO

The connection between the MJO and the AO/NAO has been investigated in several previous studies. The eastward progression of the convectively active phase of the MJO is found to be associated with a corresponding shift in the tendency and sign of the Arctic Oscillation index. The high (low) AO phase is more likely when the

TABLE 1. Skewness of the three daily indices of the AO, ZP500, and ZP50 in extended winters from 1979/80 to 2013/14, and correlations between pairs of them.

	Skewness	Correlation with ZP500	Correlation with ZP50
AO_1000	−0.09	−0.72	−0.41
ZP500	0.15	1.00	0.48
ZP50	0.38	0.48	1.00

FIG. 9. Difference of T2m correlation skill averaged over the northern polar region ($>60^{\circ}\text{N}$) between forecasts initialized with +ZP500 and those initialized with -ZP500. Vertical bars represent 95% level of confidence intervals calculated using a bootstrap resampling method. A positive difference value indicates that the +ZP500 forecast has a better skill than the -ZP500 forecast.

tropical MJO-related convection is enhanced (suppressed) over the Indian Ocean (Zhou and Miller 2005; L'Heureux and Higgins 2008). In response to a tropical forcing, the extratropical teleconnection becomes well developed in about two weeks (Jin and Hoskins 1995). This lagged relationship between a tropical forcing and the extratropical response is evident in the MJO-related teleconnection. Lin et al. (2009) found that about 2–3 pentads after the occurrence of MJO phase 3 (phase 7), which corresponds to enhanced (reduced) convection in the tropical Indian Ocean and reduced (enhanced) convection in the tropical western Pacific, a positive (negative) phase of the NAO tends to occur. A similar result was reported in Cassou (2008). The MJO phases 2–3 and 6–7 that correspond to a west–east dipole structure of the tropical convection in the Indian Ocean–western Pacific region tend to be the most effective in exciting extratropical Rossby waves (Lin et al. 2010a). A link between the MJO phase and the surface air temperature change in the Arctic was found in Yoo et al. (2011), which shows that MJO phases 4–6 are followed in 1–2 weeks by Arctic warming while MJO phases 1–2 are followed by Arctic cooling.

To see the influence of the MJO on the polar atmospheric condition, lagged composites of T2m anomalies are made for the forecasts with initial MJO phases of 3 and 6 representing the tropical dipole heating structures. Shown in Fig. 11 are the lagged composites of T2m anomalies 3 pentads after the initial condition of MJO phase 3. In the observation (Fig. 11a), we see significant cold anomalies in the Arctic area centered north of the

FIG. 10. (a) Autocorrelation of ZP500 for positive (blue) and negative (red) ZP500 cases. (b) As in (a), but for ZP50. Vertical bars represent 95% level of confidence intervals calculated using a bootstrap resampling method.

Bering Strait. This Arctic cooling is consistent with the positive NAO 2–3 pentads following MJO phase 3 as observed in Lin et al. (2009). This temperature anomaly appears at the same location of the maximum forecast skill of T2m on the S2S time scale (Fig. 4). All the three operational S2S forecasting systems are able to capture the general feature of the polar T2m cooling anomalies (Figs. 11b–d). The pattern correlations between the observation (Fig. 11a) and the model forecast T2m anomaly of ECCO (Fig. 11b), ECMWF (Fig. 11c), and NCEP (Fig. 11d) reach 0.55, 0.70, and 0.57, respectively. The predicted magnitude of the cooling, however, is weaker than the observations. Figure 12 shows the lagged composites of T2m anomalies 4 pentads after the initial condition of MJO phase 6. In the observation (Fig. 12a), warm anomalies are seen in the Arctic centered over the sector north of the Bering Strait, which is nearly opposite to the cooling after MJO phase 3 (Fig. 11a). This polar warming anomaly agrees with the negative NAO 2–3 pentads following MJO phase 7 as observed in Lin et al. (2009). The predictions hint to some warm anomalies in the polar region, but the amplitude is weaker and the location is not consistent among the three models (Figs. 12b–d). The ECCO model has a warm anomaly north of Greenland, while the NCEP system predicts a warm anomaly north of Canada. The ECMWF model has positive anomalies of more than 0.5°C north of the Bering Strait, in the same area as the observations (Fig. 12a), although they are weaker than the observations and not statistically significant. The pattern correlations between the observation (Fig. 12a) and the model forecast T2m anomaly of ECCO (Fig. 12b), ECMWF (Fig. 12c), and NCEP (Fig. 12d) are 0.34, 0.39, and 0.52, respectively.

During the hindcast period analyzed in this study, there are a total of 166 forecasts that are initialized with MJO with an amplitude greater than 1. Of that, the numbers of forecasts for different initial MJO phases are listed in Table 2. The correlation skill of T2m averaged over the northern polar area ($>60^{\circ}\text{N}$) is evaluated for the forecasts initialized with each MJO phase. Figure 13 illustrates the forecast skill as a function of lead time in pentad (y axis) and MJO phase (x axis) for the three forecast systems. This may give some indication of the dependence of polar T2m skill on the MJO phase, although the sample sizes are quite small (Table 2). It can be seen that the forecasts starting from MJO phases 6–7 do have a relatively good skill for all the three models. For the ECCO and ECMWF models, the forecasts initialized from MJO phase 3 also perform relatively better than phases 2 and 4.

In summary, the MJO influences the polar T2m through teleconnections. The S2S models appear to capture this signal to some extent, which contributes to the forecast skill in the polar region.

6. Summary and discussion

In this study, the prediction skill of T2m and Z500 in the northern polar region during the boreal winter season is assessed using the ensemble reforecast data from the ECMWF, ECCO, and NCEP operational S2S systems. The findings are summarized as follows:

- At lead time of 3–6 pentads, the forecast skill is the highest in the tropics and lowest in the Arctic. The skill over the midlatitudes is in between the tropical and Arctic skill values.

FIG. 11. Composites of T2m anomaly 3 pentads after initial condition with MJO phase 3, for (a) ERA-Interim, (b) ECCC, (c) ECMWF, and (d) NCEP. The contour interval is 0.5°C . The blue and red contours are for negative and positive T2m anomalies, respectively. The zero contour is in black. The yellow and orange areas are statistically significant at the 0.05 and 0.01 levels, respectively.

- The three models have comparable forecast skill in the northern polar region on the subseasonal time scale. Although the correlation skill values are modest in the S2S systems, this indicates the potential to obtain useful forecast information in the polar region.
- The S2S forecast skill of T2m over the Arctic is located mainly in two areas, one over the sector north of the Bering Strait and the East Siberian Sea and the other centered near the Barents Sea.
- The polar forecast skill is influenced by the phase of the NAM/AO. The forecasts initialized from a negative AO (+ZP500) are more skillful for the lead time of pentads 4–6 than those initialized from a positive AO (–ZP500). This difference in skill between posi-

tive and negative AO is likely associated with the stratosphere–troposphere coupling.

- There is evidence that the tropical MJO influences the forecast skill in the northern polar region through atmospheric teleconnections. Forecasts initialized from MJO phases 6–7 tend to have a better polar forecast skill on the S2S time scale than those starting from other MJO phases.

As seen from the above analysis, the polar prediction skill is influenced by both the AO and the MJO. It should be noted that the variabilities of the MJO and AO are not independent. A negative AO/NAO tends to occur following MJO phases 6–7 (e.g., Lin et al. 2009;

FIG. 12. As in Fig. 11, but for composites of T2m anomaly 4 pentads after initial condition with MJO phase 6.

Cassou 2008). Here we found that both the negative AO and MJO phases 6–7 lead to improved forecast skill in the polar region. How much of the AO contribution comes from the MJO and how much from the stratospheric process is an interesting question, which would need further studies to clarify.

This study confirms the result from previous studies that the predictability of the AO/NAO is dependent on its initial phase (e.g., Ferranti et al. 2015). Here we provide an explanation for this dependence with the difference in persistence of positive and negative AO. The negative AO is more persistent than the positive AO, and thus more predictable. In the analysis of section 4, the difference in the persistence between positive and negative AO is explained by the behavior of the stratospheric polar vortex. Another possible mechanism

that could explain the difference in predictability between the positive and negative AO is the nonlinearity of the AO/NAO response to the tropical MJO forcing. Through observational analysis and numerical experiments, Lin and Brunet (2018) found that the tropical forcing related to MJO phases 6–7 can excite a negative NAO with stronger amplitude than a positive NAO associated with the same tropical forcing but of opposite sign. It is likely that both the nonlinearity in extratropical response to the MJO and the connection to the

TABLE 2. Number of forecasts initialized with different MJO phases.

MJO phase	1	2	3	4	5	6	7	8
Forecasts	15	20	26	16	26	18	24	21

FIG. 13. T2m skill averaged $>60^{\circ}\text{N}$ as function of initial MJO phase for the model of (a) ECCC, (b) ECMWF, and (c) NCEP. Contour interval is 0.2.

stratospheric polar vortex contribute to the difference in predictability between positive and negative AO/NAO.

In the three S2S systems analyzed, both the ECMWF and NCEP systems use atmosphere–ocean coupled models (Vitart 2004; Saha et al. 2014), whereas the ECCC system utilizes an atmospheric-only model (Lin et al. 2016). The results obtained in this study show that the three systems have comparable prediction skill in the northern polar region. This indicates that the air–sea coupling processes that are particularly relevant for polar predictions have not been well represented in these S2S models. Another aspect of these models is their representation of the stratosphere. Both the ECMWF and NCEP models have a higher top (0.01 hPa for ECMWF and 0.02 hPa for NCEP) and more vertical levels (91 levels for ECMWF and 64 levels for NCEP) and thus a better resolved stratosphere than the ECCC model, which has a total of 40 vertical levels with the top at 2 hPa. From Fig. 9, we do see that the ECMWF and

NCEP models have a more significant difference of T2m skill for pentads 4–6 between the forecasts initialized with negative and positive AO than the ECCC model. As the AO influence on polar forecast skill likely comes from the stratosphere, this implies that a better resolved stratosphere would result in improved S2S forecast skill in the Arctic region.

The ECMWF model has been shown to have a much better MJO forecast skill than the other two models (e.g., Vitart 2017; Lim et al. 2018). However, the three models have a comparable forecast skill in the polar region on the S2S time scale with lead time of 4–6 pentads. This indicates that the superior MJO forecast skill in the ECMWF model has not been transformed to an improved polar forecast skill in pentads 4–6. It is possibly due to systematic errors in the midlatitude basic state in weeks 3–4, which causes errors in the MJO teleconnection response. Shown in Fig. 14 are biases of Z500 for the three models averaged for days 1–15 and days 16–30.

FIG. 14. Systematic error of Z500 averaged during (left) days 1–15 and (right) days 16–30 for (a),(b) ECCC, (c),(d) ECMWF, and (e),(f) NCEP. Contour interval is 10 m. Contours with negative values are dashed. The zero contour is omitted.

As can be seen, both the ECCC and ECMWF models tend to have positive Z500 biases in the Northern Hemisphere middle latitudes and the polar region north of Greenland, whereas the NCEP model has negative biases mainly in the middle latitudes. The biases increase in magnitude from days 1–15 to days 16–30. As discussed in Lin and Brunet (2018), the extratropical response to the MJO is sensitive to the position and strength of the midlatitude westerly jet. Therefore, in order to improve the polar forecast on the S2S time scale, it is important to have well predicted MJO and its associated teleconnections, which may be achieved by reducing the model bias in the extratropical basic flow.

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