Assessing Seasonal Predictability Sources and Windows of High Predictability in the Climate Forecast System, Version 2

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ABSTRACT

The representation of ENSO and NAO are examined in the Climate Forecast System, version 2 (CFSv2), reforecasts with a focus on the physical processes related to teleconnections and predictability. CFSv2 predicts ENSO well, but an eastward shift of the tropical Pacific sea surface temperature (SST) anomalies is evident. Although it appears minor on the global scale, the shift in convection and the large-scale wave train affects the model prediction of regional climate. In contrast, NAO is predicted poorly. The anomaly correlation coefficient (ACC) between the model ensemble mean and the observation is 0.27 during 1982–2010, and the ensemble spread is large. The representation of three sources of NAO predictability—SST, the stratospheric polar vortex, and the Arctic sea ice concentration—is investigated. It is found that the link between tropical Pacific SST and NAO is not well represented in CFSv2, and that the tropospheric–stratospheric interactions are too weak, both contributing to the poor prediction of NAO. Additionally, the impact of ENSO and NAO on prediction skill of CFSv2 in boreal winter is analyzed in terms of the spatial ACC of geopotential height. Active ENSO events exhibit larger prediction skill than neutral years, especially during the ENSO+/NAO− and ENSO−/NAO+ winters. Spatial patterns of prediction skill are also examined, and larger skill of geopotential height and 2-m air temperature is found outlined by the nodes of the PNA pattern, consistent with the large signal-to-noise ratios associated with the ENSO teleconnection.

1. Introduction

Seasonal prediction, along with subseasonal prediction, has long been considered a gap in current forecasting capability (Weisheimer and Palmer 2014; Vitart 2014). Skilful seasonal predictions can provide useful information for decision-makers across a variety of sectors, ranging from energy and agriculture to transportation and public health (National Academies of Sciences, Engineering, and Medicine 2016). Improved seasonal prediction skill is thus of profound socioeconomic value, and physics-oriented model evaluation is an indispensable part of the effort.

Skilful seasonal prediction is related to several sources of predictability, including inertia, external forcing, and patterns of variability (National Research Council 2010). Recurrent modes of low-frequency variability, which arise from the interaction between different components of the climate system, such as El Niño–Southern Oscillation (ENSO), the Madden–Julian oscillation (MJO), and the annular modes [including the North Atlantic Oscillation (NAO)] (National Research Council 2010) are of focus herein. These patterns of variability evolve on the subseasonal and longer time scales, and their canonical evolution and the associated “teleconnections” may allow forecasters to infer changes of the climate system from its present state. Owing to such sources of predictability, it has been proposed that windows of potential predictability of the atmospheric state exist on all time scales (Hoskins 2013). The present study will focus on ENSO, the NAO, and midlatitude weather regimes and will evaluate their representations and impacts on the seasonal prediction skill in the Climate Forecast System, version 2 (CFSv2).

ENSO is a prominent coupled mode involving the tropical atmosphere and ocean. Although the associated SST anomalies largely occur in the tropics, ENSO induces climate anomalies in many parts of the planet and plays an important role in seasonal prediction (Power et al. 1999; Yuan 2004; Brönnimann 2007; Mariotti 2007; Grimm and Tedeschi 2009). For example, anomalous convection in the central to eastern tropical Pacific
excites a Rossby wave train spanning from the North Pacific to North America [known as the Pacific–North American (PNA) pattern (Wallace and Gutzler 1981; Barnston and Livezey 1987)], modulates the midlatitude storm track, and leads to precipitation and temperature anomalies in North America (Cole and Cook 1998; Wang et al. 2007). Coupled global models in recent years exhibit high skill in predicting ENSO from a month to 2 years in advance (e.g., Rosati et al. 1997; Jin et al. 2008; Luo et al. 2008; Kim et al. 2012).

The NAO is the dominant mode of variability over the North Atlantic, characterized by a seesaw pattern in boreal winter sea level pressure between the Azores high and Icelandic low (Hurrell et al. 2003). Both phases of the NAO are associated with the intensity and structure changes of the midlatitude jet over the North Atlantic and impact weather and climate over eastern North America and western Europe (Hurrell 1995; Scaife et al. 2008). The NAO is a regional manifestation of the Arctic Oscillation (AO), or the northern annular mode (NAM), which is considered the dominant mode of variability in the Northern Hemisphere extratropics (Thompson and Wallace 1998). Previous studies (e.g., DeWeaver and Nigam 2000; Hurrell et al. 2003) suggested that the internal dynamics of the atmosphere, particularly eddy feedback, plays an important role in the development and maintenance of the NAO, which implies the NAO’s limited predictability. Other studies revealed the link between the NAO and blocking or Rossby wave breaking and emphasized the positive and negative phases of the NAO as two North Atlantic weather regimes (e.g., Benedict et al. 2004; Woollings et al. 2010). Weather regimes are recurrent, slowly evolving atmospheric patterns (e.g., Reinhold and Pierrehumbert 1982) typically lasting several days to a few weeks, and a prolonged weather regime serves as a source of predictability for extended-range forecasting.

In addition to the atmospheric internal dynamics, the NAO is influenced by several sources of predictability, including SST, stratospheric processes, and Arctic sea ice (Scaife et al. 2014; Smith et al. 2016; Yang et al. 2016). Although the air–sea interaction over the North Atlantic is dominated by the atmospheric forcing of the SST, significant SST anomalies were found preceding the NAO by several months (Cayan 1992; Frankignoul et al. 1998; Okumura et al. 2001; Czaja and Frankignoul 2002). In particular, the North Atlantic tripole SST pattern helps to maintain or strengthen the NAO by modulating transient eddy feedback (Kushnir et al. 2002; Peng et al. 2003; Pan 2005). Tropical Pacific SST forcing, such as seen during ENSO, may influence the NAO through the stratosphere (Toniazzo and Scaife 2006; Ineson and Scaife 2009; Bell et al. 2009). Vertically propagating Rossby waves into the stratosphere may disturb the mean flow, which in turn leads to downward-propagating signals into the troposphere affecting the NAO (Baldwin and Dunkerton 2001; Ineson and Scaife 2009; Scaife 2010). Owing to such predictability sources, recent studies showed that the NAO could be predicted skillfully using either a dynamical model (Scaife et al. 2014; MacLachlan et al. 2015) or a statistical model (Wang et al. 2017). However, the prediction skill of the NAO is very poor in some prediction systems. It has been shown that CFSv2 has difficulty predicting the NAO (e.g., Kim et al. 2012), but the cause of the model deficiencies is not clear.

The present study aims to analyze the representation of ENSO and the NAO in the CFSv2. We will focus on the physical processes related to the teleconnection or predictability sources and aim to reveal the possible cause of model deficiency and provide useful information on model improvements. In addition, we will investigate how these low-frequency climate modes are related to the windows of high predictability in CFSv2. The rest of the paper is organized as follows. Section 2 briefly describes the datasets and methodology. Section 3 evaluates ENSO, the NAO, and the North Atlantic weather regimes in CFSv2 against the CFS reanalysis. The windows of high/low predictability in space and time are examined in section 4, followed by a summary/discussion in section 5.

2. Data and methodology

a. Data

The reforecasts produced from the NCEP CFSv2 were analyzed (Saha et al. 2014) to assess the sources of seasonal predictability. The atmospheric model is executed at T126L64 spectral resolution coupled to the ocean, land surface, and sea ice (Saha et al. 2014). The ocean component includes the Global Ocean Data Assimilation System (GODAS) and Modular Ocean Model, version 4 (MOM4; Griffies et al. 2003), and the sea ice comes from an interactive three-layer model. The CFSv2 employs the Noah land surface model, which contains four soil levels (Ek et al. 2003).

The CFSv2 reforecasts are initialized every fifth day at four times (0000, 0600, 1200, and 1800 UTC) during 1982–2010. The National Centers for Environmental Prediction (NCEP) Climate Prediction Center (CPC) releases an official seasonal prediction on the third Thursday of each month, making the seventh day of each month the last runs available to the seasonal forecasts (Saha et al. 2014). To stay consistent with the CPC operational forecasts, the “November release” of the reforecasts will be used to forecast the winter (DJF)
mean, which includes 28 members (8 October–7 November every fifth day; operational releases of 9-month runs are four times a day, allowing more ensemble members to be used for an official seasonal prediction). The 28-member ensemble is used in most of our analyses as lagged ensembles of 20+ have been demonstrated to increase the wintertime seasonal prediction skill (Riddle et al. 2013). One member is used to illustrate the troposphere–stratosphere connection on the synoptic time scale (see Figs. 7 and 8).

The geopotential heights (Z), 2-m temperature (T2m), mean sea level pressure (MSLP), and sea ice concentration (SIC) from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) are used to assess the CFSv2 reforecasts. The CFSR includes the assimilation of atmospheric, ocean, and land surface observations, and has high horizontal resolution (T574L64). Here, the CFSR data are coarsened to match the resolution of the CFSv2 reforecasts (T126L64). In addition, we use the Optimum Interpolation Sea Surface Temperature, version 2 (OISST; Reynolds et al. 2002), and the Global Precipitation Climatology Project (GPCP; Adler et al. 2003) to verify the sea surface temperature (SST) and precipitation rate (PRATE), respectively. The OISST and GPCP are also coarsened to be consistent with the CFSv2.

The Niño-3.4 SST index and the Southern Oscillation index (SOI) are used to represent ENSO. An NAO index is calculated as the difference in the standardized SLP between Reykjavik, Iceland, and Lisbon, Portugal (Jones et al. 1997). A cutoff of ±0.5 standard deviation is used to select the ENSO and NAO years in composite analysis.

b. Performance metrics

The anomaly correlation coefficient (ACC) is calculated to evaluate the model prediction skill. The ACC is calculated by

\[
\text{ACC} = \frac{\text{Cov(Forecast, Observations)}}{\sqrt{\text{Var(Forecast)} \times \text{Var(Observations)}}}
\]

The metric evaluates the anomalies of the forecast and observations, which are defined with respect to the long-term mean derived from the reforecasts and observations, respectively, and no further bias correction was performed for the assessment of forecast skill for simplicity. Composite means of spatial ACC are calculated using the Fisher z transformation as correlation is not an additive quantity (Murphy and Katz 1985; Silver and Dunlap 1987).

The Heidke skill score (HSS) is used to verify temperature forecast in the form of tercile-based categorical probabilities (below, near, or above average). The HSS is computed as

\[
\text{HSS} = \frac{NC - E}{T - E},
\]

where NC is the number of correct forecasts, T is the total number of forecasts, and E is the number of forecasts expected to verify by random chance (i.e., 33.3%). The signal-to-noise (S2N) ratio is also used to determine the spatial characteristics of predictability in the CFSv2. Here, the S2N ratio is defined as the ensemble mean standard deviation divided by the ensemble member standard deviation with respect to the ensemble mean.

3. Evaluation of prominent climate modes

a. El Niño–Southern Oscillation

We first examine the prediction skill of ENSO in the CFSv2. Figures 1a and 1b show the winter seasonal mean Niño-3.4 index and the SOI, respectively, from the CFSv2 ensemble mean and the OISST/CFSR. The CFSv2 predicts the wintertime Niño-3.4 index quite well, with a correlation coefficient of 0.86 over the time period 1982/83–2009/10. The correlation is slightly higher than in Kim et al. (2012) (r = 0.85), probably because of the larger ensemble size used here. Nonetheless, the correlation is still lower than the ECMWF Sys4 (Kim et al. 2012). Additionally, the ensemble spread is very small, indicating a strong agreement among individual ensemble members. The correlation (0.73) for the SOI between the CFSv2 and CFSR is lower than that of the Niño-3.4 index, but still exceeds the 99% confidence level. Figure 1 concludes that the winter seasonal mean ENSO is highly predictable a month in advance by the CFSv2.

Tropical precipitation is closely related to tropical SST (Graham and Barnett 1987; Neelin and Held 1987). Warm SST anomalies may induce enhanced convection in the tropics, producing a Rossby wave train that propagates into the extratropics and modifies the atmospheric circulation in remote regions. To evaluate how this tropical–extratropical interaction is represented in the model, singular value decomposition (SVD) (Bretherton et al. 1992; Björsnsson and Venegas 1997) was performed to examine the covariability between extratropical 200-hPa geopotential height (Z200) and tropical SST. The SVD analysis was carried out for individual ensemble members, followed by averaging the singular vectors and squared covariance fractions (SCF) over all ensemble members. Figure 2b shows the ensemble mean of individual member’s leading modes.
and the leading mode from the CFSR and OISST is shown in Fig. 2a for comparison. The SVD analysis of the CFSR reveals the ENSO pattern as the leading mode in the SST field, which consists of anomalies over the tropical east Pacific and Indian Ocean and anomalies of the opposite polarity over the west Pacific in a horseshoe pattern. The leading mode in Z200 is characterized by the PNA pattern spanning from the tropical east Pacific to North America, which induces precipitation and temperature anomalies via thermal advection or modulation of the storm track (Leathers et al. 1991).

The CFSv2 reproduces the large-scale SST and 200-hPa geopotential height patterns over the Pacific and North America. However, an eastward shift in the SST and PNA patterns is evident in comparison to the OISST and CFSR. To better illustrate this shift, the composite anomalies of 200-hPa geopotential height based on the Niño-3.4 index were constructed for the CFSv2 forecast and CFSR, with the centers of action (local maximums/minimums) highlighted (Fig. 3a). The tropical Pacific high and North Pacific low shift eastward by about 11° (∼1000 km). The displacement of the low over North America is hardly discernible (∼3° longitude), probably because transient eddy feedback and barotropic instability of the mean flow play an important role in maintaining this center of action, which tends to make extratropical low-frequency perturbations geographically fixed (Simmons et al. 1983; Jin et al. 2006).

Figure 3b shows the composite anomalies of SST and PRATE averaged between 20°S and 20°N for the CFSv2 and OISST/GPCP. Positive anomalies of SST and PRATE are present over the central to eastern tropical Pacific. Figure 3b demonstrates an apparent eastward shift for both SST and PRATE in the CFSv2. Although appearing small on a global scale, the displacements have important implications for regional climate anomalies.

Other discrepancies in Fig. 2 are discernible in addition to the eastward displacement. For example, the CFSR shows a tripole pattern over the west Pacific, while the CFSv2 shows a dipole pattern of weaker amplitude. In addition, the anomalous high and low over North America associated with the PNA+ pattern have
an eastward extension illustrating a negative NAO over the North Atlantic in the CFSR (Cassou and Terray 2001), but the CFSv2 fails to capture this feature.

The SCF describes the percentage of covariability explained by each pair of coupled modes in the SVD analysis. The ensemble mean SCF of the leading mode is 88.8%, and the range of SCF among ensemble members is 84.4%–92.1%, skewing toward greater values, while the SCF for the CFSR/OISST is 85.25%. The larger SCF in the CFSv2 implies that the model overestimates the contribution of the ENSO and PNA pattern to climate variability or underestimates the contribution of the other teleconnection patterns related to tropical SST. This is consistent with the poor representation of the NAO–tropical SST link in the CFSv2 discussed in section 3b.

b. The North Atlantic Oscillation

Next, we examine the ability of the CFSv2 to predict the NAO, followed by analyzing the known predictability sources of the NAO in the CFSv2. The NAO is closely related to precipitation and temperature anomalies over west Europe and eastern North America (Hurrell 1995; Scaife et al. 2008), and skillful monthly to seasonal forecast of the NAO is thus important for regional climate prediction in these regions.
Figure 4 shows the time series of the DJF seasonal mean NAO index derived from the CFSR, the CFSv2 ensemble mean, and the spread among ensemble members. Poor agreement between the CFSR and CFSv2 ensemble mean is evident, as the Pearson correlation coefficient is only 0.27. In addition, a large spread is found among the CFSv2 ensemble members. The ACC in the present study is slightly higher than that in Kim et al. (2012) ($r = 0.21$) for the same time period, most likely due to the larger ensemble size used here. Nevertheless, both studies show NAO prediction is far less skillful than that of the ENSO in the CFSv2.

The poor prediction skill of the NAO in the CFSv2 suggests that the sources of NAO predictability may not be well represented in the model. We next examine three sources of NAO predictability in the CFSv2: SST, stratospheric polar vortex, and Arctic sea ice. Variables representing these three predictability sources were used as predictors in a multiple linear regression model by Wang et al. (2017), which skillfully predicted the winter NAO index ($r = 0.76$ over the time period 1980–2015).

1) Sea Surface Temperature

The NAO composite anomalies of SST and MSLP are shown in Fig. 5 from the CFSR (Figs. 5a,d) and the CFSv2 ensemble mean for the same years (Figs. 5b,e). The former can be regarded as the “truth,” while the latter illustrates the CFSv2 prediction. The MSLP composites from the CFSR are characterized by strong anomalies over the Arctic and anomalies of the opposite polarity in the midlatitudes. Two centers of action are present in the midlatitudes, one over the North Atlantic and one over the North Pacific. The anomalies project to the zonal mean, indicating the link between the NAO and the NAM. The NAO+ atmospheric circulation anomalies are accompanied by the classic tripole SST pattern over the Atlantic (Rodwell et al. 1999; Sutton et al. 2000), along with weak positive anomalies in the tropical eastern Pacific and strong negative anomalies in the tropical central and western Pacific. During NAO−, the atmospheric circulation anomalies are nearly opposite to those in NAO+ with a slightly less well-defined SST tripole pattern over the Atlantic. Cold SST anomalies are found over the equatorial east Pacific and positive SST anomalies are found over the west Pacific, resembling the La Niña. This seems to contradict the findings of SVD analysis in Fig. 2a, which suggested El Niño events are associated with NAO−. Further analysis showed that the three strongest NAO− years occurred during weak to moderate La Niña events and contributed to the composite cold SST signals. Warm SSTs reside in most of the Pacific during NAO− with removal of these three years (not shown), suggesting a possible nonlinear relationship between the ENSO and the NAO.

The CFSv2 predicts a north–south dipole of MSLP over the Atlantic during NAO+ with the midlatitude center of action displaced poleward and eastward (Fig. 5b). Further analysis suggests that the dipole pattern is mainly due to the strong and well predicted NAO+ in 1988 (not
shown), and the dipole pattern weakens substantially with the removal of 1988. A dipole pattern is hardly discernible over the North Atlantic in the CFSv2 prediction during the NAO− years (Fig. 5e), consistent with the poor NAO prediction skill. Additionally, the MSLP anomalies over the North Pacific are present but are weaker than in the CFSR for both NAO phases (note the different contour intervals and ranges in the CFSv2 and CFSR composites). The predicted SST anomalies in the CFSv2 are broadly consistent with those in the CFSR during NAO+ except over the eastern Pacific (Fig. 5b). During NAO−, the SST anomalies in the CFSv2 resemble those in the OISST over the western tropical Pacific, but opposite to those in the OISST over the central Pacific and are too weak over the eastern Pacific and the Atlantic.

To examine the intrinsic NAO pattern in the CFSv2, we constructed the composite anomalies for each ensemble member based on the NAO index derived from the corresponding ensemble member and took the ensemble mean (right column of Fig. 5). The composites show patterns similar to the CFSR, with a north–south dipole of MSLP over the North Atlantic during both phases, as well as the appropriate Atlantic SSTs. However, the MSLP anomalies are much weaker in the CFSv2, and the equatorward node of the NAO is meridionally confined compared to the CFSR. Additionally, the North Pacific dipole is very weak or nonexistent. The SST anomalies over the equatorial Pacific are weakly positive or close to zero, in contrast to those in the OISST. In summary, the CFSv2 is unable to skillfully predict the NAO and the associated circulation anomalies despite the decent SST prediction (Figs. 5b and 5e) and a reasonable intrinsic NAO pattern (Figs. 5c and 5f) in the CFSv2. The large Pacific SST discrepancies associated with the intrinsic NAO (Figs. 5c and 5f) imply that the poor NAO prediction may be partly attributed to the disconnection of the Pacific SST to the Atlantic atmospheric circulation.

2) STRATOSPHERIC POLAR VORTEX

The importance of the stratosphere in producing NAO signals have been suggested in previous studies (Scaife et al. 2005; Toniazzo and Scaife 2006; Ineson and Scaife 2009; Bell et al. 2009). Here, we examine the polar vortex in the stratosphere using 70-hPa geopotential height (Z70). Figure 6 shows the same composites as Fig. 5 but for Z70 and Z200. The CFSR (left column) displays nearly opposite signals in Z70 and Z200 between NAO+ and NAO−, and both clearly exhibit an annular pattern. A stronger stratospheric polar vortex is associated with NAO+, and vice versa. The CFSv2 predicts (middle column) much weaker anomalies of the correct sign over the Arctic region. In addition, the centers of action are displaced off the pole, and the midlatitude anomalies are weaker and less coherent or annular compared to the CFSR. In contrast to the weak tropical signals in the CFSR, strong negative anomalies in Z70 are found in the tropics in NAO+ (Fig. 6b), which can be attributed to the cold SST anomalies over the tropical Pacific (Fig. 5b).

The right column in Fig. 6 shows the CFSv2 composites based on the NAO index derived from individual ensemble members, as in the right column of Fig. 5. The CFSv2 polar vortex representation during NAO resembles the CFSR but the magnitude is weaker (note the different contour intervals), especially over the Pacific sector, making the overall pattern less annular. Overall, Fig. 6 suggests that the CFSv2 represents a realistic albeit weaker link between the NAO and the stratospheric polar vortex but has difficulty predicting the variability of the stratospheric polar vortex.

To further illustrate the stratosphere–troposphere interaction during the NAO, Fig. 7 shows the time–pressure
cross sections of zonally averaged geopotential height composite anomalies (80°W–30°E) along 65°N, where downward propagation from the stratosphere would be expected (Baldwin and Dunkerton 2001; Scaife 2010; Ineson and Scaife 2009). Figures 7a and 7b show the cross section for the CFSR NAO+ and NAO−, respectively, while Figs. 7c and 7d are the same but for the CFSv2 prediction, in which only one ensemble member was used in order to prevent smoothen of synoptic-scale signals. Additionally, the intrinsic NAO signals from the same ensemble member are shown in Figs. 7e and 7f for comparison. Downward and upward propagation of signals between the stratosphere and the lower troposphere are clear in the CFSR (Baldwin and Dunkerton 2001) (Figs. 7a,b). The CFSv2 prediction (Figs. 7c,d) shows downward propagation of anomalies into the middle and lower troposphere, but the stratospheric signals are much less persistent. In contrast, the composites of the intrinsic NAO (Figs. 7e,f) suggest that the CFSv2 captures the persistent stratospheric anomalies but the signals are more barotropic in nature and show less downward propagation except in late winter. Overall, Figs. 6 and 7 suggest that the stratospheric polar vortex is poorly predicted in the CFSv2, and that the stratosphere–troposphere interaction may be too weak in the CFSv2. The latter statement is further supported by the long-term mean eddy meridional heat flux ($\bar{\omega'}T$) at 100 hPa between 45° and 75°N (Fig. 8), which is proportional to the vertical component of the Eliassen–Palm (EP) flux. Strong negative biases in the meridional heat flux are found in late winter (January–February) in the long-term mean, both phases of the ENSO, and both phases of the NAO in the CFSv2, indicating weak vertically propagating wave activity.

FIG. 5. Composite anomalies of SST (K, shading) and MSLP (hPa, contours) for (a) OISST/CFSR during NAO+. (b) CFSv2 ensemble mean during NAO+. (c) CFSv2 intrinsic NAO+. (d)–(f) As in (a)–(c), but for the negative phase of NAO. Contour intervals for MSLP: −3 to 3 hPa every 0.5 hPa for the CFSR and CFSv2 intrinsic NAO, and −0.5 to 0.5 hPa every 0.1 hPa for the CFSv2 prediction. SST anomalies that are statistical at a 90% confidence interval are shown in hatching for the OISST and CFSv2 prediction.
from the troposphere to the stratosphere. Further analysis shows that the strong negative biases are mainly present in the North Pacific sector. Since tropospheric wave forcing is an important trigger for stratospheric circulation anomalies, which may then propagate downward and affect the troposphere (Baldwin and Dunkerton 2001; Ambaum and Hoskins 2002; Scaife et al. 2005), the weak vertical wave activity may explain the poor prediction of the stratospheric polar vortex and further contribute to the poor prediction of the NAO.

3) ARCTIC SEA ICE

SIC, as a source of NAO predictability (Yang et al. 2016; Screen 2017), is also examined. The diabatic heating anomalies associated with SIC variability may impact the overlying atmospheric circulation (Deser et al. 2007), and a negative feedback between SIC and NAO has been discovered in observational studies (Strong et al. 2009; Strong and Magnusdottir 2011). Composite analysis was performed, as in Figs. 5 and 6 (not shown). A large area of positive anomalies exists between Newfoundland and Greenland during NAO+, and nearly opposite SIC anomalies are found in NAO−. Overall, the prediction of SIC by the CFSv2 is reasonable and does not appear to be a major factor for the model’s poor performance in the NAO prediction.

c. The North Atlantic weather regimes

Weather regimes are strongly related to extreme weather and climate anomalies (e.g., Robertson and Metz 1990; Michelangeli et al. 1995; Hannachi and Trendafilov 2017), and as stated earlier, weather regimes serve as a source of predictability. Multiple studies have revealed four weather regimes over the
North Atlantic, including the Atlantic ridge (AR), Scandinavian blocking (BL), NAO+, and NAO− (e.g., Vautard 1990; Cassou 2010). Here, K-means clustering is applied to the 500-hPa geopotential height (Z500) daily anomalies (with the seasonal cycle removed). Cluster analysis for the CFSv2 was applied to the collection of individual ensemble members as a single realization as the ensemble mean smooths out the synoptic-scale signals.

Figure 9 shows the four weather regimes in the CFSR (top four panels) and the CFSv2 (bottom four panels). The CFSv2 reproduces the spatial pattern of each regime reasonably well, but some discrepancies are discernible. More specifically, the blocking high in the AR is smaller in the CFSv2; the southern node shifts eastward in the NAO−; and the BL pattern exhibits a stronger Rossby wave train. In the CFSR, the AR occurs least often, followed by NAO−, BL, and NAO+ occurring most often. The CFSv2 produces the four weather regimes in the same order of increasing frequency, but overestimates the frequency of occurrence of AR and NAO− while underestimating BL and NAO+.

Although the CFSv2 reproduces the climatology of the weather regimes reasonably well, the prediction of the seasonal frequency of occurrence is very poor. Figure 10 shows the time series of the frequency of occurrence of each weather regime in the winter season from the CFSR and the CFSv2. The CFSR shows large variability from year to year for each regime. It is interesting to note the opposite peaks between AR and BL, and between NAO− and NAO+. A decreasing trend in frequency of occurrence of NAO+ is discernible, which is consistent with a wider and slower jet stream associated with the Arctic warming (Screen and Simmonds 2013; Barnes 2013; Cohen et al. 2014). The CFSv2 is unable to skillfully predict the frequencies of occurrence of the weather regimes. The correlation between CFSR and the CFSv2 ensemble mean frequency of occurrence was 0.04, 0.11, −0.05, and 0.02 for AR, NAO−, BL, and NAO+, respectively. These low correlations and large ensemble spreads reiterate the low predictability over the North Atlantic region and are consistent with the poor performance of the model in predicting the NAO.
4. Windows of high predictability

We next pursue how these low-frequency climate modes modulate prediction skill. First, we take a look at the windows of predictability in time to examine during which phases of ENSO and NAO we expect greater skill. Second, we examine the windows of predictability in space to see where the model is more skillful in producing winter forecast.

a. Windows of predictability in time

Figure 11 displays how the ENSO impacts winter Northern Hemisphere (NH; 20°–80°N, 0°–359°E) geopotential height prediction skill and how the NAO, plus the combination of the ENSO and NAO, impacts the geopotential height prediction skill in the North Atlantic–European sector (NA/EUR; 30°–80°N, 80°W–30°E). The spatial correlation is calculated for the DJF seasonal mean field annually within the domain at each pressure level (1000–1 hPa), and then composite means are derived for the different ENSO or NAO phases using the Fisher Z-transformation.

Figure 11a shows the Northern Hemisphere winter prediction skill of geopotential height for El Niño, La Niña, and neutral years. The prediction skill is larger during El Niño years than that in La Niña or neutral phased years at each pressure level, especially in the stratosphere. The difference between El Niño and neutral years is statistically significant at a 95% confidence interval using a Student’s t test at each pressure level. The prediction skill during La Niña is statistically significant and larger than the neutral years in most of the troposphere. The larger skill in tropospheric geopotential height during active ENSO years seen here agrees with previous studies that have shown larger prediction skill of multiple variables during increased tropical forcing, such as from the ENSO or the MJO (Qin and Robinson 1995; Jones et al. 2004; Kim et al. 2012; Jones et al. 2015), but Fig. 11a also shows that La Niña does not lead to more skillful prediction of the stratosphere in the CFSv2.

Figure 11b is the same as Fig. 11a, but for the NAO over the NA/EUR sector. The ACC during NAO+ is smaller than that of NAO− and neutral years within most of the troposphere, and the neutral years have the largest skill at the surface, but no statistically significant results arise for any group. Overall, this is consistent with the poor NAO prediction in the CFSv2.

As stated in section 1, the ENSO is one source of NAO predictability (Scaife et al. 2014; Smith et al. 2016). Therefore, we examined how the combination of ENSO and NAO impacts the North Atlantic prediction skill. Figure 11c shows the skill composites for NAO years that coincide with El Niño years (4 NAO−, 4 NAO+). The mean skill during 1982–2010 is shown as the benchmark. The ACC during NAO− is higher than the long-term mean and NAO+ at most pressure levels.
FIG. 9. (a)–(d) CFSR Z500 composites based on K-means clustering into the four known Atlantic weather regimes: Atlantic ridge (AR), NAO−, Scandinavian blocking (BL), and NAO+. (e)–(h) As in (a)–(d), but using all ensemble members from the CFSv2.
NAO+ has lower skill than the long-term mean within the troposphere, but increases with skill into the stratosphere. The model skill for NAO years that occur during the negative phase of ENSO are shown in Fig. 11d (5 NAO+, 6 NAO−). At most pressure levels below 3 hPa, NAO+ has larger skill than both NAO− and the long-term mean, and the ACC during NAO− is significantly lower than the long-term mean above 40 hPa. In summary, higher prediction skill of geopotential height should be expected over the Atlantic/Eurasia domain during NAO+ years coinciding with El Niño or during NAO− years coinciding with La Niña.

We do recognize that the sample size of the ENSO/NAO results is rather low as only 28 years of the reforecast are available, which is a limitation of this study. Nevertheless, it is interesting to see how the ENSO and the NAO modulate prediction skill of the CFSv2.

b. Windows of predictability in space

To examine the windows of high predictability in space, the Pearson correlation of geopotential height between the CFSv2 ensemble mean forecast and the CFSR was computed at each grid point. Figure 12a shows the two-dimensional correlation map for DJF Z200. Strong positive and nearly homogenous correlation values prevail in the tropics, which can be attributed to the strong coupling between the atmosphere and ocean in the tropics and the weak temperature gradient nature of the tropical atmosphere. In the extratropics, strong correlation values are found over the North Pacific and North America, corresponding to the nodes of the PNA, while lower predictability exists in regions over the North Atlantic and Eurasia. It is interesting to note that despite the poor prediction of NAO, strong skill is still present poleward of 60°N over some regions.

The pattern of high correlation values for 850-hPa geopotential height (Z850) largely resembles that for Z200 in the extratropics, consistent with the barotropic structure of low-frequency teleconnection patterns. In particular, the high correlation values over the North Pacific and North America outline the nodes of the PNA pattern. The correlation maps in Figs. 12a and 12b were also calculated for individual CFSv2 ensemble members. The ensemble mean of the correlation maps for
individual ensemble members produced similar patterns but with a weaker magnitude.

The spatial variability of prediction skill can be further demonstrated by the S2N ratio for DJF Z200 (George and Sutton 2006). High S2N ratios over the North Pacific and North America, are again consistent with the PNA nodes (Fig. 12c). In addition, a band of high S2N extends from the Eurasian continent to North America along 60°N, which is possibly linked to the NAM. The absence of a similar pattern in the ACCs of Z200 indicates the poor agreement in the NAM between the CFSv2 ensemble mean and the CFSR despite the high S2N. In addition, the S2N is relatively low over the North Atlantic, consistent with the poor NAO skill in the CFSv2.

The high ACCs for Z850 and Z200 imply skillful prediction of surface weather. Figure 12d is the two-dimensional HSS for the DJF tercile forecast of 2-m temperature (T2m). In general, HSS is higher in the tropics and subtropics (equatorward of 30°N) than in higher latitudes. In addition, high HSSs are found over northwestern North America and south of the Hudson Bay, which may be tied to the circulation anomalies via temperature advection or cloud-radiative effect.

5. Summary and discussion

The representation of the ENSO, NAO, and weather regimes were evaluated within the NCEP Climate Forecast System, version 2 (CFSv2). The CFSv2 predicts both the Niño-3.4 and the SOI well, with the former being more skillful than the latter. The CFSv2 also predicts the ENSO teleconnection, particularly the PNA pattern, reasonably well. However, SVD analysis suggested that the ENSO and the PNA pattern are overproduced in terms of squared covariance fraction in the model. An eastward shift was also found in tropical SST anomalies, tropical precipitation anomalies, and the PNA nodes over the Pacific, which may affect the prediction skill of regional climate anomalies.

Although recent studies suggested the NAO is predictable on seasonal and longer time scales, the CFSv2 has difficulty predicting the NAO skillfully. The correlation between the predicted NAO index and that
derived from the CFSR is very low. Further analysis suggested that the CFSv2 realistically represents the link between the NAO and Atlantic SST and predicts the SST anomalies over the Pacific and Atlantic reasonably well. However, the composites of MSLP/SST based on the NAO index in the CFSv2 (or the intrinsic NAO composites) suggest that the link between the tropical Pacific SST and the NAO is not realistically represented in the CFSv2, and that the MSLP center of action over the North Pacific is largely absent. This indicates a disconnection between the Pacific sector and the NAO in the CFSv2. In addition, the interaction between the troposphere and stratosphere is too weak, and the stratospheric polar vortex is poorly predicted by the CFSv2, which also contributes to the poor prediction of the NAO. Consistent with the poor NAO prediction, the seasonal frequency of occurrence of weather regimes is not skillfully predicted.
despite the realistic spatial patterns of the weather regimes in the CFSv2.

We also examined how the ENSO and the NAO modulate the prediction skill of the CFSv2. Higher prediction skill of geopotential height is found throughout the troposphere in El Niño and La Niña years than in the neutral years, and the model skill also tends to be higher in the stratosphere in El Niño years than in La Niña or neutral years. Significant differences in prediction skill were not found for NAO1 or NAO2 because of the poor model performance in predicting the NAO. Subgroupings were also analyzed for NAO1 and NAO2 during El Niño and La Niña years separately. Higher skill exists in a majority of the troposphere during El Niño/La Niña and NAO1/La Niña/NAO+ than during El Niño/NAO+ or La Niña/NAO−. Spatially, the tropics and subtropics have generally higher prediction skill than the higher latitudes, and greater prediction skill and high S2N (i.e., windows of high predictability in space) in Z200, Z850, and T2m exist corresponding to the PNA nodes while relatively low prediction skill was found over the North Atlantic.

The evaluation of widows of high predictability is solely based on the CFSv2, and some results, such as the low prediction skill over the North Atlantic, are likely model dependent. It is possible that regions of high predictability will emerge around the NAO nodes if a model can skillfully predict the NAO. In addition, it is desirable to evaluate other climate modes or other time scales, such as the QBO and the MJO.

The poor prediction of the NAO in the CFSv2 can be attributed to the poor representation of the two major sources of predictability, the Pacific SST and the stratospheric polar vortex. The two issues may be intertwined and are both related to the model mean state biases. For example, the CFSv2 underpredicts the stratospheric jet (50-hPa $U$) over the North Pacific by $\sim$40% (Fig. 13a), which could be a reason for poor communication between the Pacific and Atlantic. Castanheira and Graf (2003) found that the MSLP in the North Pacific and North Atlantic is strongly correlated when the stratospheric polar vortex is strong. The weak or nearly absent center of action in MSLP over the North Pacific and the zonally restricted equatorward node of the NAO in the CFSv2 (right column in Fig. 5) are consistent with the circulation pattern in the regime of the weak stratospheric polar vortex shown in Castanheira and Graf (2003). The weak stratospheric polar vortex, however, cannot be explained by the weak vertical wave propagation (Fig. 8), which should contribute to a stronger polar vortex because of the lack of heat flux into the stratosphere. This suggests that some other poorly represented physical processes cause the negative biases of the stratospheric jet.

Large biases in the tropospheric jet are also found in the CFSv2 (Fig. 13b). The jet is displaced poleward over the Eurasia–North Pacific sector, and is underestimated over the North America–North Atlantic sector. Consistently, the storm track is displaced poleward over the Pacific and underestimated over the North Atlantic (not shown). These biases have a few implications. First, the eddy–mean interaction, which plays an important role in the NAO dynamics (DeWeaver and Nigam 2000;
Hurrell et al. 2003), is underestimated in the CFSv2. Second, the poleward displaced jet over the Pacific may weaken the extratropical stationary wave response to tropical forcing (Sardeshmukh and Hoskins 1988; Scaife et al. 2017), which may weaken both the tropospheric and stratospheric pathways of the ENSO–NAO teleconnection (Butler et al. 2014). In particular, Garfinkel et al. (2013) suggested that the troposphere–stratosphere coupling is sensitive to the latitude of the tropospheric jet. We further examined the sudden stratospheric warming (SSW) in the CFSv2 following the methods of Thompson et al. (2002), as the troposphere–stratosphere interaction is especially strong during SSW (Baldwin and Dunkerton 2001; Scaife et al. 2016; Butler et al. 2015). During the time period of analysis, 8 SSW events occurred in El Niño years, 9 occurred in La Niña years, and 3 occurred in neutral years (19 total). The CFSv2 underproduces SSW events (13 events), and produces twice as many SSW events during El Niño (8 events) than La Niña (4 events). The underestimated SSW events, especially during La Niña years, again reflect the poor representation of the troposphere–stratosphere interaction in the CFSv2.

The poor connection between the troposphere and stratosphere is a common issue in global models and may be attributed to various factors (Gerber and Polvani 2009; Charlton-Perez et al. 2013; Riddle et al. 2013; Furtado et al. 2013). These abovementioned physical processes warrant further investigations for the improvement of the CFSv2.

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