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Improvement of 1-month lead predictability of the wintertime AO using a realistically varying solar constant for a CGCM

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ABSTRACT: The impact of solar constant variation on the predictability of the Arctic Oscillation (AO) is investigated in terms of 1 month lead hindcast data obtained from a coupled general circulation model. The 1 month lead hindcasts produced from a realistic initial solar constant experiment (Solar Run, SR) and from a climatological solar constant experiment (Control run, CR) are comparatively analysed. The 1 month lead hindcasts were initiated from mid-November, mid-December and mid-January of each year for the period 1980–2009. The hindcast of the SR showed better skill than that of the CR in terms of forecasting not only the AO index but also the atmospheric circulation pattern related with the AO. This shows that the prescription of realistic solar constant as the initial condition is necessary for improved AO prediction.

KEY WORDS Arctic Oscillation; predictability; solar constant; 1-month lead forecast; coupled general circulation model (CGCM)

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1. Introduction

Recently, anomalous warm events and cold surges have been increasing rapidly during the boreal winter. Many investigations reported that these anomalous temperature variations are closely related with the large-scale disturbance associated with the Arctic Oscillation (AO), thus implying the importance of the AO forecasting during the season (e.g. Cohen *et al.*, 2010). According to previous studies, the AO is caused by various reasons such as the variations of tropical and subtropical sea surface temperature (e.g. Hoerling *et al.*, 2001; Kim and Ahn, 2012), snow depth (e.g. Gong *et al.*, 2004) and solar activity (e.g. Kodera, 2003). Among these, we focused on the role of solar activity.

The importance of solar activity on the AO has been suggested by recent studies based on observed and model-simulated results (e.g. Ruzmaikin and Feynman, 2002; Kodera, 2002, 2003; Tourpali and Schuurmans, 2003; Tourpali *et al.*, 2005; Baldwin and Dunkerton, 2005; Kryjov and Park, 2007; Kuroda *et al.*, 2007; Huth *et al.*, 2007; Kodera *et al.*, 2008). Among them, the modelling studies by Tourpali and Schuurmans (2003) and Tourpali *et al.* (2005), Kuroda *et al.* (2007), and Ineson *et al.* (2011) verified the AO response to solar activity mainly by comparing the atmospheric circulation under high and low solar conditions. However, as these studies did not assess the influence of solar activity on the long-range AO prediction, we examined the potential to improve the AO predictability by using the initial value of realistic solar constant in 1 month lead hindcast.

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2. Data

The model used in this study is the Pusan National University Coupled General Circulation Model (PNU CGCM), one of the participant models of the APEC Climate Center Multi Model Ensemble Seasonal Prediction System (http://www.apcc21.net). The model consists of NCAR Community Climate Model version 3 (CCM3) atmospheric general circulation model (AGCM), GFDL Modular Ocean Model version 3 (MOM3) oceanic general circulation model (OGCM) and Elastic Viscous Plastic (EVP) model for sea ice (Sun and Ahn, 2011).

Two experiments, a solar run and a control run (SR and CR, respectively), were performed under the same initial and boundary conditions. The only difference between the two is that the SR was integrated with realistically varying initial solar constant for the hindcast, while the CR was run with a fixed solar constant (1367 W m^{-2}). The 1 month lead hindcasts for December, January and February, which were initiated from the 15^{th} of November, December and January of each year, respectively, for the period 1980–2011, were used to verify the 1 month lead predictability of the wintertime (December-February mean, DJF-mean hereafter) AO. In this study, the first 15 or 16 days (0 month lead) of the integrations were discarded, and only the next 1 month hindcasts were analysed.

The observational data used for verification and evaluation of the AO predictability were NCEP/DOE reanalysis II (hereafter R2) (Kanamitsu *et al.*, 2002). The observed solar constant

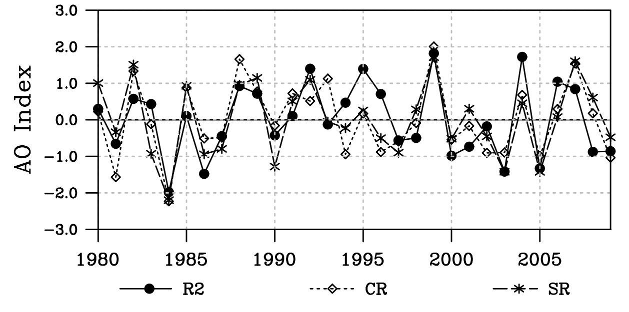

Figure 1. Temporal variation of the AO index during 1980–2009. Solid, dotted and dashed lines represent the observation, CR and SR, respectively.

(total solar irradiance, TSI) that was used as solar forcing was taken from the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC), Switzerland (Fröhlich, 2000).

3. Results

We defined the AO as the first principal mode of DJF-mean geopotential heights of the all standard pressure levels poleward of the 20 ° N obtained from the combined empirical orthogonal function (CEOF) analysis (Wheeler and Hendon, 2004). The CEOF analysis is designed to empirically infer the characteristics of the space-time variations of the various field variables. This method is useful to interpret physical meaning between multivariate data (Sparnocchia *et al.*, 2003). Prior to computing CEOF, geopotential height field of each level was zonally averaged at every latitudinal point. The first modes of the R2, SR and CR, which explained over 80% of each total variance, were clearly separated from the second mode (not shown). The large variance of the first mode is due to the zonal mean equivalent barotropic structure of the AO. Figure 1 shows the first PC timeseries of the R2, SR and CR, which are considered as the AO indices since the correlation coefficients between the first PC of CEOF and classical AO index based on sea level pressure anomaly are significant at the 99% level of confidence. The AO indices of the SR and CR captured reasonably well the time variation of the observation. The temporal correlation coefficient of the first PC timeseries between the R2 and SR and between the R2 and CR were 0.71 and 0.51, respectively, which were both significant at the 99% level of confidence. The time series of the SR AO index was more similar to the R2 than that of the CR. A remarkable improvement of variation in the SR compared to the CR was seen from 1992 to 1994, in particular. The difference in correlation coefficient between SR/R2 and CR/R2 was 0.2, which was statistically significant at the 89% level of confidence based on Fisher's transformation.

A statistically significant difference between the two experiments was also found in the atmospheric fields regressed onto the AO index. It is known that the meandering of jet stream has an impact on the regional climate in the mid-latitudes and it depends on the phase of the AO (Kim and Ahn, 2012). To verify the characteristics of upper level jet associated with AO, the regressed 200 hPa zonal wind onto the AO index is shown in Figure 2. In the observation, the positive AO phase was related to the strengthened polar jet and the weakened subtropical jet such as the Pacific jet and the Atlantic jet. The regressed zonal wind patterns simulated by the SR and CR were in good agreement with observation. However, the distribution in the SR was closer to the observation. For example, the westward shifted easterly core over the Atlantic and the weakened negative anomaly of the North Pacific represented in the zonal wind pattern of the SR were closer to the observation. The pattern correlation of the SR used to estimate the similarity of pattern quantitatively was higher than that of the CR, 0.88 and 0.81, correspondingly.

The stratospheric circulation anomaly altered by solar forcing propagates downward to the surface through the troposphere over time (Tourpali *et al.*, 2005; Ineson *et al.*, 2011). Figures 3 and 4 indicate the AO signal appeared at surface. The R2 sea level pressure (SLP, Figure 3) showed a typical AO pattern, which was characterized by a meridional seesaw pattern oscillating between the midlatitude and the polar regions. Although the CR well described SLP distribution of the R2, the SR was more realistic in the sense that the eastward shifted North Atlantic centre in the CR moved to the west in the SR and the overestimated anomalous high over the North Pacific in the CR moderated slightly in the SR, as in the R2. Huth *et al.* (2007) insisted that the Pacific area is strongly affected by the solar activity due to possible mutual coupling between the AO and the El Niño-Southern Oscillation (ENSO). The distribution of surface air temperature (Figure 4) has a zonally asymmetric thermal structure and it corresponds with the result from Thompson and Wallace (2000). The comparison of pattern correlations for SLP and surface air temperature between the

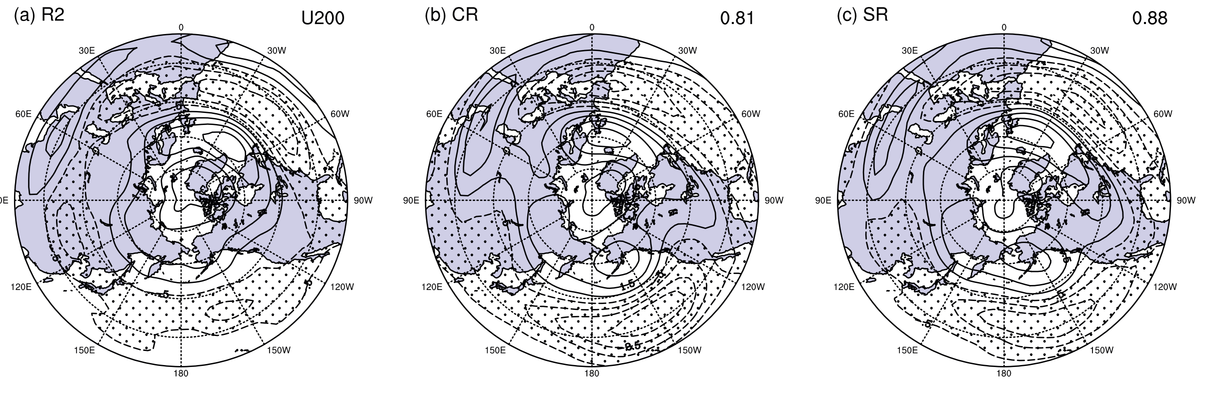

Figure 2. Regressed fields of 200 hPa zonal wind against the time series of the AO index. The right-cornered value above each plot's upper boundary indicates the spatial correlation co-efficient between the observation and the model output. Stippling indicates areas where anomalies are negative. Contour interval is 1.0 m s^{-1}. This figure is available in colour online at wileyonlinelibrary.com/journal/met

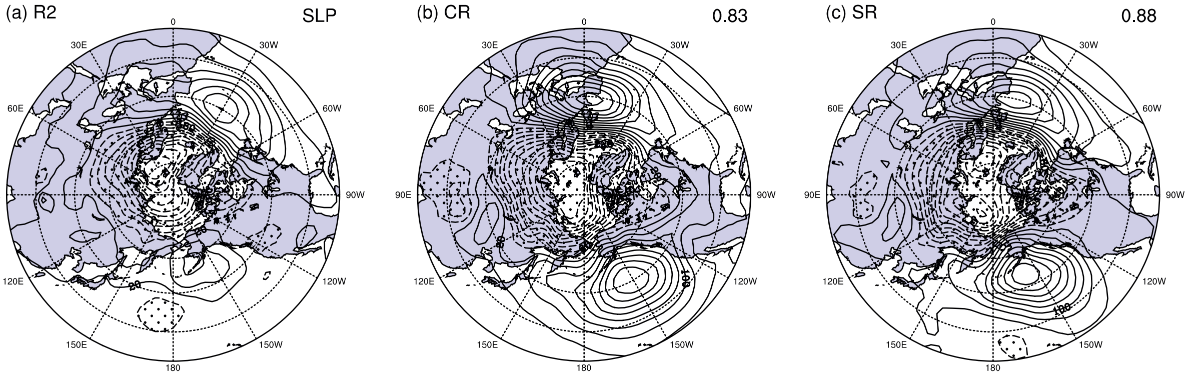

Figure 3. Same as Figure 2, except for the sea level pressure (SLP). The right-cornered value above each plot's upper boundary indicates the spatial correlation co-efficient for the SLP between the observation and the model output. Stippling indicates areas where anomalies are negative. Contour interval is 40 hPa. This figure is available in colour online at wileyonlinelibrary.com/journal/met

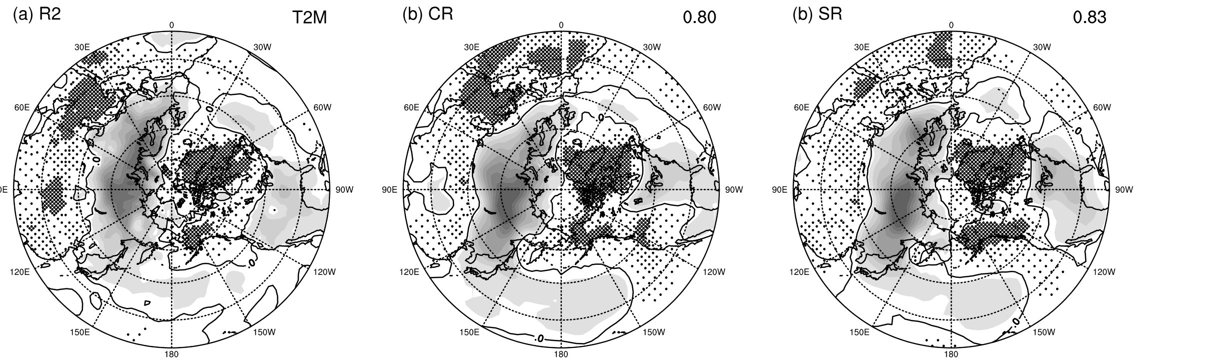

Figure 4. Same as Figure 3, except for 2 m temperature. The right-cornered value above each plot's upper boundary indicates the spatial correlation co-efficient for the 2 m temperature between the observation and the model output. Shading and dotted areas indicate positive and negative anomalies, respectively. The zero contour is plotted as thick solid line. Contour interval is 0.2 °C.

two runs revealed that these differences were also statistically significant.

The strength of the polar vortex is considered as a good indicator of the AO. That is, the improvement of forecast skill for geopotential height over the polar cap is identical to the betterment of AO predictability. The improvement of AO predictive skill of the SR can be found by assessing the predictability of polar vortex. Figure 5 reveals the relative skill score of polar vortex for the SR against the CR. The skill score was calculated from the method of Roff *et al.* (2011) and the score of the CR was set as the reference forecast. A positive value of skill score denotes an improved forecast in the SR with respect to the CR, namely, a reduced mean square error. The improvement was not large until 15 days of lead time (figure not shown), after which the geopotential height over the polar cap was pronouncedly enhanced in the SR, particularly at the mid of the 1 month lead. Consequently, the improvement of AO predictability at 1 month lead time was attributed to the enhanced daily forecast skill of geopotential height in the SR over the polar cap.

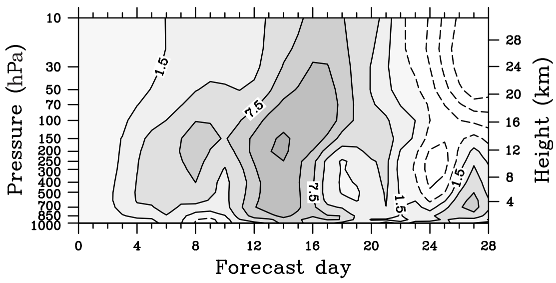

Figure 5. Skill score of geopotential height over the polar cap (poleward of 65 ° N) for the SR relative to the CR. The score represents the change of forecast error as the percentage and the shading areas indicate increased forecast skill in the SR relative to the CR.

4. Summary and conclusion

This study revealed that the boreal winter AO predictability can be improved by imposing a realistically varying solar constant as the initial condition of a coupled model such as PNU CGCM. The significantly improved AO forecast skill in SR resulted from the enhanced daily forecast skill of polar vortex by the SR. That is, a more realistic atmospheric response in the upper level to the realistically varying initial solar constant affected all levels of the atmosphere *via* stratosphere-troposphere coupling (e.g. Baldwin and Dunkerton, 2005), thereby improving the AO forecast. Our results verified that the AO can be influenced by solar activity as well as by atmospheric convection associated with tropical sea surface temperature changes (e.g. Hoerling *et al.*, 2001) and the cryospheric variation at high latitude (e.g. Gong *et al.*, 2004). Therefore, it is important to consider the realistic initial solar constant for more enhanced AO prediction.

The coupled model responds only to variations of TSI and there are no changes in stratospheric ozone in response to solar variability, so the mechanism must depend almost entirely on the variation of solar forcing (Meehl *et al.*, 2008). Since the upper level of the model used in this study was limited to 2.9 hPa and the model did not have 11 year ozone variation, meridional thermal contrasts simulated by both the SR and CR might be weaker than the values observed in the stratosphere (data not shown). These weak temperature gradients can weaken the simulations of polar vortex regarded as an AO proxy. Such a deficiency in model stratospheric forcing may have caused the discrepancy between simulated and observed AO (Scaife *et al.*, 2005; Kodera *et al.*, 2008). In spite of the model's limited vertical resolution and the lack of proper photochemical reaction responding differently at various ranges of solar spectrum as the solar constant varies, it is worth noting that the model can raise the predictability of the AO forecast by imposing a realistic solar constant as the initial condition.

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