AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL071584

Key Points:
- The snow-AO relationship has only emerged in the 1970s
- It should be rather analyzed as distinct snow-NAO and snow-PNA links
- It involves a stratospheric pathway which can be modulated by the QBO

Supporting Information:
- Supporting Information S1

Correspondence to:
H. Douville,
herve.douville@meteo.fr

Citation:
Douville, H., Y. Peings, and D. Saint-Martin (2017), Snow-(N)AO relationship revisited over the whole twentieth century, *Geophys. Res. Lett.*, *44*, 569–577, doi:10.1002/2016GL071584.

Received 13 OCT 2016
Accepted 1 DEC 2016
Accepted article online 4 DEC 2016
Published online 12 JAN 2017

Snow-(N)AO relationship revisited over the whole twentieth century

H. Douville[1], Y. Peings[2], and D. Saint-Martin[1]

[1]Centre National de Recherches Météorologiques, Météo-France/CNRS, Toulouse, France, [2]Department of Earth System Science, University of California, Irvine, Irvine, California, USA

Abstract Several studies suggest that the Siberian snow cover in fall is a source of predictability of the Arctic Oscillation (AO) in winter. Although a plausible dynamical mechanism was proposed, the robustness of this relationship was recently challenged. Here we use two atmospheric reanalyses to revisit the snow-AO relationship and its modulation across the whole twentieth century. While our results support a stratospheric pathway mechanism, they show that the snow-AO relationship has only emerged in the 1970s and should be rather analyzed as a contrasted multidecadal behavior of the North Atlantic Oscillation (NAO) and Pacific North America pattern. They confirm that the quasi-biennial oscillation is a plausible candidate for the modulation of the snow-(N)AO relationship across the twentieth century, but they further show that this modulation might be a purely stochastic effect. Therefore, they emphasize the limitations of any empirical prediction of the (N)AO only based on snow and/or sea ice predictors.

1. Introduction

The Arctic Oscillation (AO), also known as the Northern Annular Mode, is the dominant mode of variability of the Northern Hemisphere atmospheric circulation in winter [*Thompson and Wallace*, 1998]. It is causally related to, and thus partially predictive of, weather patterns in locations many thousands of miles away, including many of the major population centers of Europe and North America. The AO index is usually defined by projecting mean sea level pressure (SLP) or geopotential height (Z) at 1000 hPa north of 20°N on their respective loading pattern. Yet the AO paradigm has been challenged due to the lack of correlation between the surface pressure variability at its centers of action [*Ambaum et al.*, 2001] and might be rather considered as two regional modes of variability, namely, the North Atlantic Oscillation (NAO) and the Pacific North America (PNA) pattern. Because the climatological features over the two ocean basins are at different latitudes, an increase in the AO (or NAO) does not imply a simple strengthening of the circumpolar flow, but strong tropospheric jets in the North Atlantic and a weakened jet in the North Pacific. Since the AO paradigm is however still widely used in the climate community and the debate is not closed, we will use the (N)AO notation to refer to either AO or NAO in the continuation of this study.

The (N)AO is a fundamental internal mode of atmospheric variability on a wide range of timescales. Despite its stochastic nature, statistical or dynamical long-range forecasting systems have attained useful levels of predictability in recent times [*Cohen and Fletcher*, 2007; *Scaife et al.*, 2014], suggesting that the (N)AO is modulated by slowly evolving external forcings and/or lower boundary conditions. In particular, both observational evidence and idealized numerical sensitivity experiments relate the fall Eurasian/Siberian snow cover extent to the subsequent winter (N)AO over recent decades [e.g., *Cohen and Entekhabi*, 1999; *Gong et al.*, 2003; *Fletcher et al.*, 2009]. The proposed mechanism involves a wave mean-flow interaction through a complex stratospheric pathway described in detail by *Cohen et al.* [2007]. Yet this teleconnection is still poorly captured by most general circulation models [*Hardiman et al.*, 2008; *Furtado et al.*, 2015], and the attribution of the recent improvement in dynamical winter (N)AO predictions remains a debate [e.g., *Déqué and Batté*, 2015]. Some numerical experiments suggest that the snow-(N)AO teleconnection is highly sensitive to the simulation of the winter climatological flow [e.g., *Peings et al.*, 2012]. This sensitivity implies a possible modulation of the snow influence by other modes of climate variability. In particular, *Peings et al.* [2013] have suggested that the quasi-biennial oscillation (QBO) in the equatorial stratosphere can either reinforce or mitigate the (N)AO response to the snow forcing, thereby representing a stochastic modulation of the snow-(N)AO relationship.

The present study aims at revisiting the robustness and/or stability of the snow-(N)AO relationship by taking advantage of the availability of two global atmospheric reanalyses covering the whole twentieth century. All data sets are detailed and evaluated in section 2. The key results are described in section 3, while more details and additional results are provided in the supporting information. Conclusions are drawn in section 4. The main finding is that the snow-(N)AO relationship shows consistent interdecadal fluctuations between both twentieth century reanalyses. Such a modulation can arise from purely stochastic noise and/or from a stochastic influence of the QBO, with obvious implications for the design and calibration of empirical (N)AO seasonal predictions.

2. Data Sets

Two state of the art global atmospheric reanalyses covering the whole twentieth century are used in the present study: an update of the NOAA 20th Century Reanalysis (20CR, 1851–2014) [*Compo et al.*, 2011] and the recent European Centre for Medium-Range Weather Forecasts (ECMWF) 20th Century Reanalysis (ERA-20C, 1900–2010) [*Poli et al.*, 2016], respectively. Both reanalyses are driven by observed monthly mean sea surface temperature and sea ice concentration. For the sake of homogeneity (even if the global number of assimilated observations drops before the 1940s), they only assimilate surface pressure observations, as well as marine wind observations in ERA-20C. Yet they show consistent synoptic weather and seasonal anomalies in the northern extratropics when compared with more recent reanalyses [*Poli et al.*, 2016] and are therefore useful to document the snow-(N)AO relationship over the whole twentieth century.

We only use the 20CR (version 2c) global atmospheric reanalysis for describing the fall snow cover variability over Siberia [35–60°N/40–180°E]. This choice is supported by our evaluation of the former version of 20CR against in situ observations [*Peings et al.*, 2013] as well as by a comparison with satellite data over recent decades (Figure S1 in the supporting information). While the reanalyses show a weaker multidecadal variability, the recent increase in the fall snow cover extent found in the visible imagery has been diagnosed as a spurious shift [*Brown and Derksen*, 2013] and the year-to-year variability is much more consistent between 20CR and the other data sets. Note that our snow cover index (SCI) is the average of October-November (rather than October only) monthly anomalies since both months show a similar correlation with the subsequent winter (December-January-February (DJF)) AO index (Figure S2).

The wintertime extratropical circulation is summarized by three tropospheric indices and a simple low stratospheric index. The AO index is defined by projecting DJF mean SLP anomalies north of 20°N on their first EOF (empirical orthogonal function). A positive (negative) AO index corresponds to low (high) pressure anomalies throughout the polar region and high (low) pressure anomalies across the subtropical and midlatitudes. Similarly, the NAO index is defined by projecting DJF mean Z500 anomalies over North Atlantic on their loading pattern. The PNA index is computed as a standardized DJF Z500 quadripole following the early definition of *Wallace and Gutzler* [1981]. Finally, the strength of the early winter polar vortex in the lower stratosphere is characterized by the November to January (NDJ) Z10 anomalies averaged north of 60°N.

Given the assimilation of surface observations only, it is crucial to first check the quality of the twentieth century reanalyses against the more comprehensive ERA-Interim reanalysis (ERAI, 1979–2014). Both ERA-20C and 20CR show consistent and realistic interannual variability of the DJF (N)AO and PNA over recent decades [*Ouzeau et al.*, 2011; *Poli et al.*, 2016], including a consistent snow-(N)AO relationship in the lower and midtroposphere (Figure S3). More surprisingly, ERA-20C also shows a reasonable interannual variability of the stratospheric polar vortex (e.g., 0.83 correlation with ERAI for the NDJ north polar cap Z10 anomalies). It should be here emphasized that 20CR is a multimember reanalysis and that we only used the ensemble mean of the 56 members. The synoptic to interannual variability is therefore smoother in this data set, especially in the stratosphere where there is a large intermember spread. In contrast, the single realization of ERA-20C shows a realistic snow signal at 10 hPa (Figure S3).

Not surprisingly, there is no clear QBO signal in the ensemble mean of 20CR and a poorly constrained spontaneous QBO in ERA-20C. Therefore, here we use the monthly QBO reconstruction by *Brönnimann et al.* [2007] extending back to 1900 and completed by ERAI over recent years. Based on historical pilot balloon data as well as hourly SLP data from Jakarta, it is in good agreement with the QBO signal extracted from historical total ozone data, and the maximum phases of the QBO are captured relatively well after about 1910 [*Brönnimann et al.*, 2007]. It is also very close to the QBO found in ERAI, both in phase and amplitude, over recent decades. As for the snow cover index, the QBO index is here calculated as the October-November

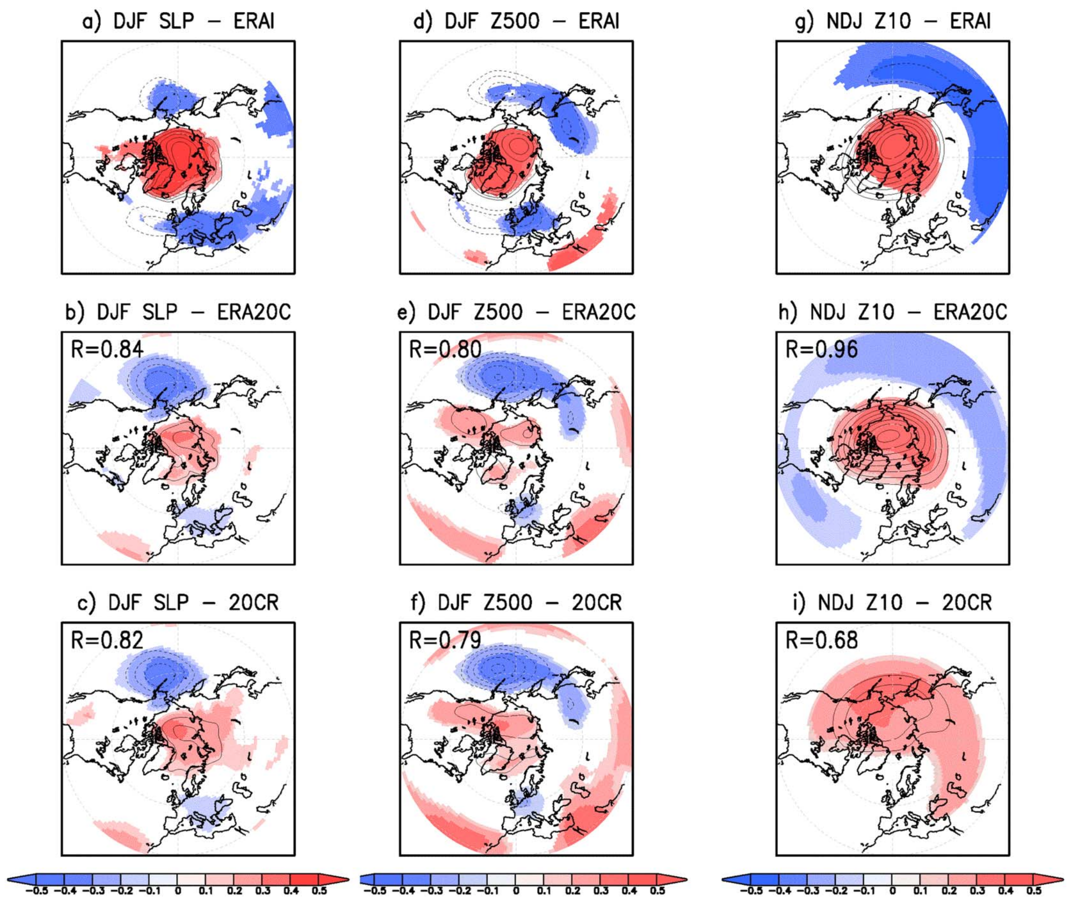

Figure 1. Regression (contours)/correlation (shading denotes p values less than 0.1 using a phase-scrambled bootstrap test) of wintertime circulation anomalies on/with former ON SCI standardized anomalies in (a, d, and g) ERAI-Interim over 1979–2014, (b, e, and h) ERA-20C over 1900–2010, and (c, f, and i) 20CR 1900–2010. Contours are every 0.5 hPa for DJF SLP (Figures 1a and 1b), every 5 m for DJF Z500 (Figures 1c and 1d), and every 20 m for NDJ Z10 (Figures 1e and 1f). R denotes the spatial correlation between the regression fields in ERA-20C or 20CR and those in ERA-Interim (as a measure of similarity).

average of the equatorial zonal winds at 30 hPa. Choosing a winter rather than fall index would, however, not change the conclusion of the study.

Finally, the ERA-20C reanalysis is also used to compute the well-known Southern Oscillation Index (positive for La Niña events and negative for El Niño events) based on the difference in normalized mean sea level pressure anomalies between Tahiti and Darwin in the tropical Pacific.

3. Results

The snow-(N)AO relationship is revisited over the 1900–2010 period by first regressing the DJF mean SLP, Z500 and Z10 anomalies in the northern extratropics on the previous fall snow cover index (Figure 1). The strong (N)AO signal found in ERAI over recent decades is weaker and hardly significant in the twentieth century reanalyses which rather show a PNA-like pattern. This result is also supported by a parallel composite analysis (Figure S5) suggesting that this North Pacific response is fairly linear. Despite the difference in the tropospheric regression patterns between ERAI and the twentieth century reanalyses, the stratospheric pathway mechanism proposed by *Saito et al.* [2001] is supported by ERA-20C (cf. Figure 1h) with an early winter (NDJ) polar vortex signal as strong and as significant than over the limited ERAI period. Moreover, lead-lag composites of monthly ERA-20C indices confirm that the stratospheric vortex signal peaks in December while the surface AO signal peaks later on in January-February (Figure S6). Therefore, Figure 1 does not challenge the conceptual model proposed by *Cohen et al.* [2007] and the causality of the snow-AO relationship.

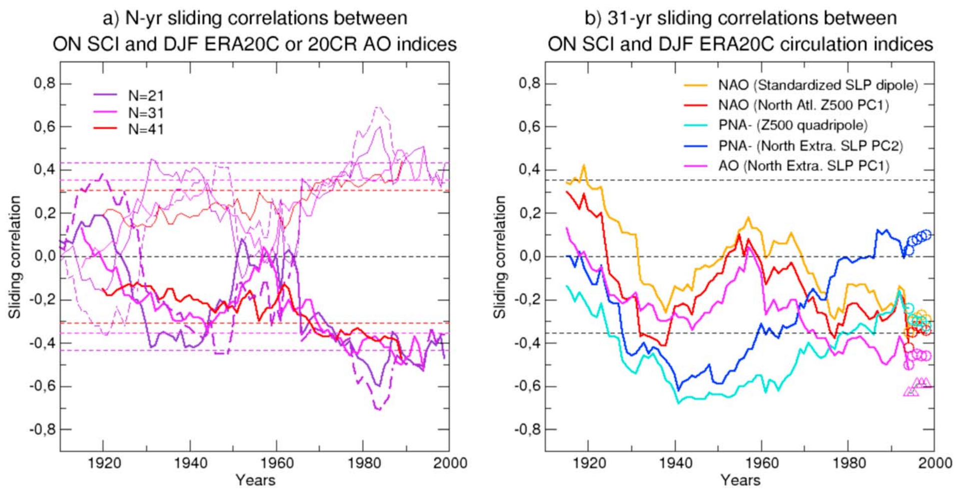

Figure 2. (a) *N* year sliding correlations between the October-November Siberian snow cover (SCI) anomalies derived from 20CR and subsequent DJF AO indices derived from ERA-20C (thick lines) or from 20CR (thin lines, *sign is reversed for the sake of legibility*) for $N = 21$ (purple), 31 (magenta), and 41 (red). Dashed curves show the 21 year sliding correlations when the October-November SCI is replaced by the October-only SCI as in Figure 3b of *Peings et al*. [2013] but using 20CR instead of the former 20CRv2 reanalysis. Dashed horizontal lines denote the 95% confidence level assuming a normal distribution and independent consecutive years. (b) Thirty-one year sliding correlations between the October-November Siberian snow cover (SCI) anomalies derived from 20CR and subsequent DJF regional circulation indices in the northern extratropics (NAO, PNA, and AO). Solid lines denote the correlations with circulation anomalies derived from ERA-20C (1900–2010), while empty circles denote the correlations with circulation anomalies derived from ERA-Interim (1979–2014). Magenta triangles denote the correlations between the ERA-Interim circulation anomalies and the ON sea ice concentration anomalies over the Barents and Kara Seas. Black dashed horizontal lines denote the 95% confidence level assuming a normal distribution and independent consecutive years. For the sake of comparison and legibility, the PNA and sea ice anomalies have been multiplied by -1.

Looking at lagged correlations over sliding windows, Figure 2a shows that the snow-AO relationship is not robust across the twentieth century. In agreement with *Peings et al*. [2013] despite the use of different data sets and indices, the relationship is strengthening across the twentieth century and peaks in the 1980s and 1990s in both ERA-20C and 20CR (the peak is even more pronounced when using October rather October-November for SCI anomalies, cf. Figure S7). This apparent strengthening reflects contrasting trends in the North Pacific versus North Atlantic sectors, namely, a weakening correlation with the PNA since the 1940s and a strengthening correlation with the NAO, at least since the 1960s. These contrasted multidecadal fluctuations support the claim of *Ambaum et al*. [2001] about the need to go beyond the zonal mean circulation and the annular mode for understanding the variability of the winter circulation in the northern extratropics.

It should be here recognized that the confidence intervals shown in Figure 2 are most likely too narrow since they assume normally distributed data and independent years. It should be also emphasized that the presence of interdecadal modulation in actual or hypothetical teleconnections is ubiquitous and can arise from stochastic noise. Following the Monte Carlo technique proposed by *Gershunov et al*. [2001], the standard deviation of the running correlations shown in Figure 2b can be compared to the range of standard deviations which is obtained by simulating $N = 5000$ sequences of running correlations between pairs of correlated white noise time series. Using the overall correlation coefficient between the SCI anomalies and each of the selected dynamical index estimated from the full record (111 years), we find that the 95th percentile of the standard deviation is comprised between 0,20 and 0,23 depending on the selected dynamical index. The actual standard deviation of the time series shown in Figure 2b is comprised between 0,15 (for the AO index) and 0,22 (for the EOF-derived PNA index) and is therefore weaker than might be expected by chance. This result means that the recent strenghtening of the snow-AO anticorrelation might be a purely stochastic variation. In other words, any empirical prediction of the winter (N)AO based on the recent anticorrelation with the Siberian snow cover in fall will be obviously overconfident.

Yet this purely statistical analysis does not exclude that there are also genuine physical causes for the modulation of the snow-(N)AO relationship. Looking at an ensemble of ten atmosphere-only simulations, using

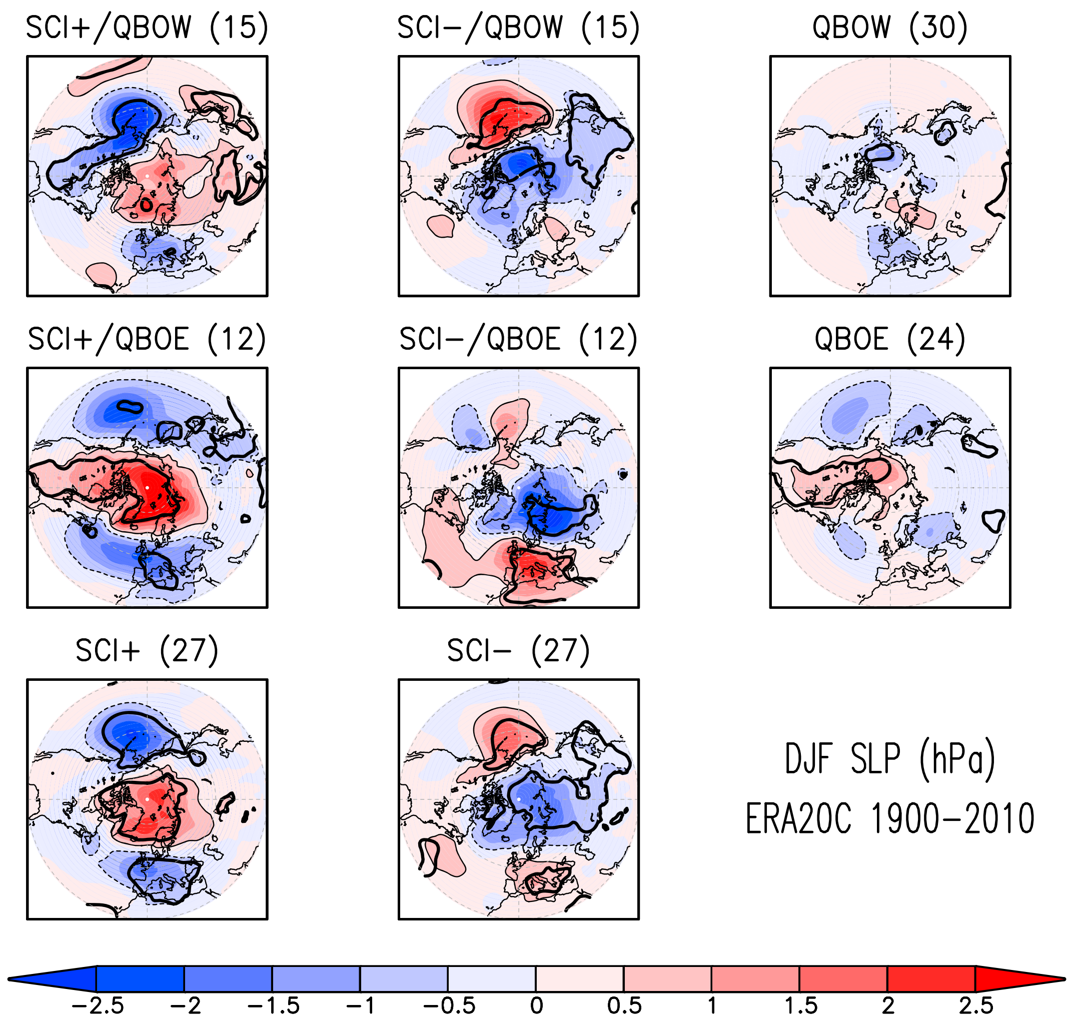

Figure 3. Subsequent DJF mean seal level pressure composites estimated from ERA-20C (1900–2010) for combined October-November SCI and QBO anomalies (above/below half a standard deviation). The number of years when the double composite criterion is reached is noted in brackets. Thick black solid lines encompass composite differences that are significant at the 90% confidence level (p value < 0.1).

the same ECMWF model and similar surface temperature and radiative forcings as in ERA-20C [*Hersbach et al.*, 2015], one can only conclude that the "observed" fluctuations of the snow-(N)AO relationship are not suitable with the simulated stochastic effect of the internal atmospheric variability (Figure S8ab). Without data assimilation, the ECMWF model might not be able to capture the subtle mechanisms whereby the Siberian snow cover in fall is likely to influence the (N)AO in winter. In particular, the model underestimates the snow influence on the surface energy budget (Figure S8c) and fails to capture the robust anticorrelation between the snow cover extent and the strength of the stratospheric polar vortex in early winter (Figure S8d). In contrast, the polar vortex influence on the winter AO is well simulated (Figure S8). Altogether, these results are consistent with the multimodel study of *Hardiman et al.* [2008] and suggest that the key ingredient for simulating the snow-(N)AO relationship is the model ability to simulate the vertical propagation of planetary waves and their interaction with the polar vortex in the lower stratosphere.

Given its robustness in ERA-20C and its absence in the ERA20CM simulations without data assimilation, the stratospheric pathway mechanism is potentially important for understanding the modulation of the snow-(N)AO relationship across the twentieth century. A plausible candidate is indeed the QBO in the equatorial stratosphere which was shown to have significant impacts on both the stratospheric polar vortex and the tropospheric extratropical circulation in winter [*Holton and Tan*, 1980; *Marshall and Scaife*, 2009]. In particular, the easterly phase of the QBO leads to the formation of a midlatitude wave guide that enhances both

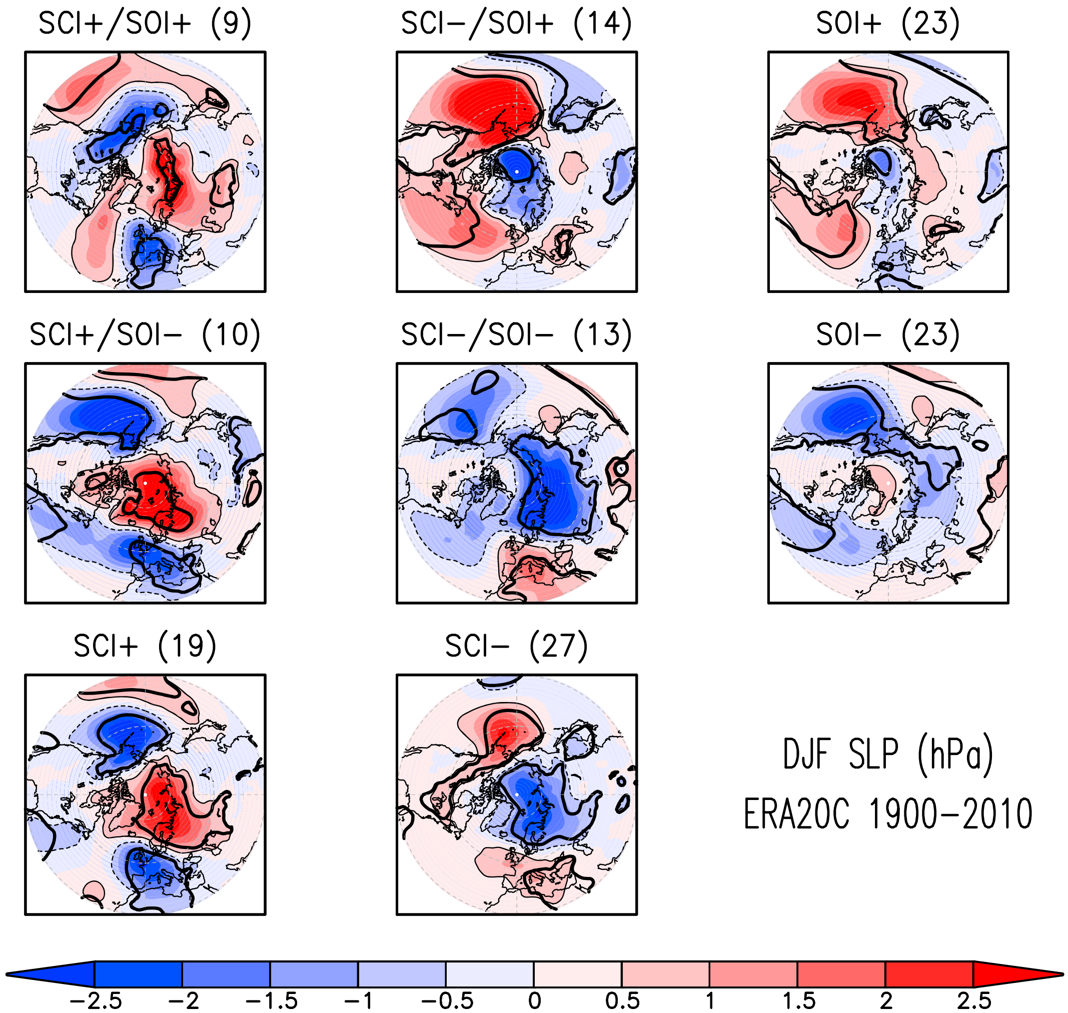

Figure 4. Subsequent DJF mean seal level pressure composites estimated from ERA-20C (1900–2010) for combined October-November SCI and SOI anomalies (above/below half a standard deviation). The number of years when the double composite criterion is reached is noted in brackets. Thick black solid lines encompass composite differences that are significant at the 90% confidence level (p value < 0.1).

the upward propagating planetary waves from the troposphere into the lower stratosphere and the northward wave propagation in the upper to middle stratosphere, thereby resulting in a more disturbed polar vortex. Yet this Holton-Tan relationship is still controversial, not captured by the ECMWF model without data assimilation, and not stable nor significant in ERA-20C (Figure S8f). Interestingly, *Garfinkel et al*. [2010] suggested that part of the recent correlation of October Eurasian snow with the January stratospheric polar vortex was due to the presence of the QBO. More recently, *Peings et al*. [2013] used the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalyses to contrast the snow-AO relationship between the 1976–2010 and the 1948–1975 periods. They showed that positive (negative) SCI anomalies over recent decades were associated predominantly with the easterly (westerly) phase of the QBO which could have favored the (N)AO response after the mid-1970s. In contrast, no single year with a possible additive effect of snow cover and QBO anomalies was found from 1948 to 1975.

This explanation is here revisited using ERA-20C and the QBO reconstruction over the whole 1900–2010 period (Figure 3). In agreement with the proposed mechanism, the response of the DJF mean SLP to the early fall snow cover anomalies is modulated by the QBO, with an enhanced NAO response for the easterly phase and an enhanced North Pacific response for the westerly phase. The number of SCI± events does not depend on the phase of the QBO over the whole ERA-20C period (Figure 3), unlike what is found in ERAI over recent decades (Figure S9). There are 15 + 12 = 27 years with either “constructive” (i.e., potentially additive) or “destructive” (i.e., opposite) snow cover and QBO effects on the subsequent (N)AO. Comparing Figure 3 with Figure S9 implies that the ratio of constructive versus destructive effects has increased over recent decades, which might indeed represent a stochastic strengthening of the snow-(N)AO relationship as hypothesized by *Peings et al*. [2013]. Note that a similar but even stronger stochastic QBO effect might also have inflated the influence of the fall Arctic sea ice extent on the winter NAO over recent decades [e.g., *Garcia-Serrano et al*., 2015; *Furtado et al*., 2016]. This is at least what is suggested by Figure S10 showing that five out of the seven fall seasons with a sea ice excess over the Barents-Kara seas experienced a westerly phase of the QBO, while 9 out of the 10 fall seasons with a sea ice deficit experienced an easterly phase.

Beyond the QBO, the El Niño Southern Oscillation (ENSO) is another plausible candidate for the modulation of the snow-(N)AO relationship given its influence on the Northern Hemisphere wintertime variability through both stratospheric and tropospheric pathways [e.g., *Butler et al*., 2014]. Figure 4 shows how the boreal winter circulation response to the fall snow forcing depends on the ENSO phase. Like for the QBO, the number of SCI± events does not depend on the phase of the ENSO. This result also holds over the ERAI period (not shown) so that the modulation of the snow-(N)AO relationship cannot be explained by a stochastic linear effect of ENSO variability. Figure 4 also indicates that the North Pacific signal found in Figure 1b is probably not an ENSO artifact since it does not vanish in the SCI+ and SCI− composites when adding a comparable number of opposite ENSO phases. Not surprisingly, the positive PNA response to a Siberian snow excess is reinforced by El Niño events in the tropical Pacific, while the negative PNA response to a Siberian snow deficit is reinforced by La Niña events. More interestingly, the North Atlantic response to the positive snow forcing is also modulated by ENSO variability. While the SCI+/SOI− composite shows significant SLP anomalies that project on the negative phase of the NAO, the SCI+/SOI+ composite shows hardly significant anomalies over the North Atlantic and Arctic oceans. This zonally asymmetric pattern suggests a tropospheric rather than stratospheric pathway and is somewhat in contradiction with the study of *Butler et al*. [2014] which suggests that the ENSO impact over the North Atlantic is dominated by a stratospheric pathway. This study is, however, based on a shorter record (1958–2013) and shows a nonlinear stratospheric polar vortex response to ENSO variability which is not so clear in ERA-20C (cf. Figure S12 showing that the ENSO signal in the polar stratosphere is hardly significant over the 1900–2010 period). Note, however, that the focus is here on the early winter season (NDJ) while *Butler et al*. [2014] explore the full winter season (NDJFM). Moreover, this apparent contradiction might be explained by the fact that the SOI− and SOI+ composites shown in Figure 4 are biased toward negative snow cover anomalies which partly offset the stratospheric response to the ENSO forcing.

4. Conclusion and Discussion

In summary, the fall snow cover reconstruction derived from 20CR and the winter mean sea level pressure fields derived from 20CR or ERA-20C suggest that the snow-(N)AO relationship is not robust across the twentieth century. It is thus risky if not reckless to predict the winter N(AO) using a simple linear regression based on a Siberian snow cover index, especially if such an empirical scheme is calibrated over recent decades only.

Nonetheless, ERA-20C supports the stratospheric pathway mechanism which has been proposed to explain the lag between the fall snow cover and the winter (N)AO anomalies, thereby also supporting the causality of the snow-(N)AO statistical relationship. Moreover, while our results indicate that the interdecadal modulation of the snow-(N)AO relationship might arise from stochatic noise only, our former hypothesis [*Peings et al*., 2013] that the QBO is partly responsible for such a stochastic modulation remains plausible. Through its potential influence on the poleward refraction of planetary waves, it can indeed either reinforce or dampen the stratospheric polar vortex response to the snow forcing.

The QBO is, however, not sufficient to fully understand the multidecadal variability of the snow-(N)AO relationship. For instance, no statistically significant QBO signal appears in the SCI composites of zonal mean zonal winds in the ERAI reanalysis (not shown), in apparent contradiction with the regression analysis shown by *Peings et al*. [2013] in their Figure 4b (it should be here noted that the snow index used in this former study was the Snow Advance Index (SAI) proposed by *Cohen and Jones* [2011] and that the QBO signal shown in their Figure 4b disappears when the SAI is replaced by the original SCI). Moreover, the Holton-Tan explanation for the QBO modulation of the snow-(N)AO relationship is not clearly supported by the combined SCI/QBO composites of the stratospheric polar vortex in ERA-20C (Figure S11). The Holton-Tan relationship is indeed not significant over the whole 1900–2010 period, and the magnitude of the polar vortex response to the snow forcing does not seem to depend on the phase of the QBO (although the statistical significance of the response is QBO dependent). What is the right interpretation of the growing Holton-Tan relationship in ERA-20C (Figure S8f)? Is it an artifact of the growing number of assimilated surface observations or a genuine modulation of the QBO influence on the polar vortex? An alternative hypothesis is that the recent strength of the Holton-Tan relationship has been—like the recent strength of the snow-(N)AO relationship—inflated by a stochastic constructive interaction between the snow and QBO effects on the polar vortex. Moreover, the spontaneous QBO simulated in ERA-20C, which does not match the reconstruction by *Brönnimann et al*. [2007], might have a spurious effect on the polar stratosphere even if there is no apparent Holton-Tan relationship in the free ECMWF model (as suggested by the ERA20CM ensemble).

Beyond the QBO, other candidates could be also at play in the modulation of the snow-(N)AO relationship, such as the main modes of low-frequency variability in the northern extratropics and/or the El Niño Southern Oscillation (ENSO) in the tropics. Our results show that ENSO is indeed likely to alter the snow influence on both PNA and NAO, but they do not suggest a strong contribution to the modulation of the snow-(N)AO relationship across the twentieth century. The role of the multidecadal variability in the North Pacific and North Atlantic has not been analyzed since even the twentieth century reanalyses are probably not long enough to draw robust conclusions. Yet the Pacific Decadal Oscillation (PDO) [*Mantua et al*., 1997] is known to modulate the interannual variability of the northern midlatitude circulation in winter. Both observational [*Gershunov and Barnett*, 1998] and numerical [*Yu and Zwiers*, 2007] studies suggest an enhanced PNA-like climate response when ENSO and PDO variability are in phase, possibly through an interaction between tropically and extratropically forced Rossby waves. More recently, *Peings and Magnusdottir* [2014] showed that the North Atlantic Multidecadal Variability (AMV) [*Ting et al*., 2009] is likely to modulate the NAO, with an opposite relationship between their polarities and a time lag of about 10–15 years. The observational evidence is limited given the available instrumental record but was supported by numerical experiments suggesting that the AMV is likely to perturb the baroclinic activity and the transient eddy-mean flow interaction over North Atlantic [*Peings and Magnusdottir*, 2015] or to trigger Rossby waves through a Gill-type response in the tropical Atlantic [*Davini et al*., 2015]. Therefore, such modes of low-frequency variability could also contribute to the modulation of the snow-(N)AO relationship shown in Figure 2. For instance, the recent strengthening of the snow-NAO anticorrelation could be partly due to the positive phase of the AMV which might favor both a negative NAO and positive snow cover anomalies over Siberia.

Finally, while the role of anthropogenic climate change is beyond the scope of the present study, Figure S13a suggests that the year-to-year variability of the fall snow cover has increased over Siberia over recent decades. This result is consistent with a parallel increase in surface air temperature variability (not shown) and might be explained by the fact that global warming (and the related retreat of Arctic sea ice in summer) is likely to increase the snowfall variability over this region in fall. Also shown in Figure S13a are the results of a subset of CMIP5 models which do confirm a possible (but much weaker than observed) modulation of the snow cover variability in the second half of the twentieth century. Yet this CMIP5 ensemble does not show any significant modulation of the snow-NAO relationship. While such a modulation appears in a five-member ensemble of CNRM-CM5 and not in a parallel ensemble of historical simulations driven by only natural radiative forcings (not shown), larger ensembles based on improved climate models [e.g., *Furtado et al*., 2015] would be necessary to draw robust conclusions about the impact of anthropogenic climate change on the snow-(N)AO relationship.

Putting it all together, our results show that there are purely stochastic and/or physically based potential contributions to the modulation of the snow-(N)AO relationship across the 20th century. Further statistical and numerical studies are necessary to better understand the multiple drivers of the (N)AO and their possible interactions. In the meantime, any empirical forecast of the (N)AO based on a few decades of observations should be used very carefully.

Acknowledgments
We are grateful to the anonymous reviewers and to J. Garcia-Serrano for insightful comments and discussions. Support for the 20CR data set was provided by the U.S. Department of Energy's Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. Monthly and daily outputs are available from http://www.esrl.noaa.gov/psd/data/20thC_Rean/. Monthly and daily outputs of both ERA-20C and ERA20CM are available from http://www.ecmwf.int. Finally, we are also thankful to S. Brönnimann for the QBO reconstruction. Please contact him directly if you are interested in this monthly data set.

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