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Key Points:
- Geomagnetic activity correlates positively with NAM for the entire twentieth century during easterly QBO
- Early and late winter NAMs respond to geomagnetic activity very differently
- Holton-Tan relation is valid only in early winter and is strongest in 30 hPa height

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Effect of geomagnetic activity on the northern annular mode: QBO dependence and the Holton-Tan relationship

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Abstract Mutually conflicting results have been presented in earlier studies on the long-term relation of geomagnetic activity (GA) and the winter northern annular mode (NAM) and its modulation by quasi-biennial oscillation (QBO). Some studies have found a stronger positive relation in the easterly phase of the QBO, while in other studies a stronger positive relation was found in the westerly phase of the QBO. Using QBO reconstruction from the beginning of the twentieth century we find that the QBO modulation of the GA-NAM relation is temporally variable, which explains the earlier, seemingly differing results. Positive relation is found to be valid in the easterly QBO phase at 30 hPa for the whole twentieth century. We also find that the QBO at 30 hPa better represents the Holton-Tan relation for the surface circulation and that the Holton-Tan relation is only observed during early/mid winter, while an anti-Holton-Tan relation is found in the late winter for strong geomagnetic activity. These results emphasize the systematic response of NAM to particle precipitation during the entire twentieth century and underline the importance of considering the preconditioning of the atmosphere when studying the solar-related effects upon climate.

1. Introduction

Several recent studies have given evidence that geomagnetic activity can affect Northern Hemisphere winter climate by modulating atmospheric circulation in the stratosphere and troposphere [see, e.g., *Lu et al.*, 2008b; *Baumgaertner et al.*, 2011; *Seppälä et al.*, 2013]. In majority of these studies, geomagnetic activity has been used as a proxy for the medium energy particles precipitating into the atmosphere [*Seppälä et al.*, 2009]. The proposed mechanism which links the particle precipitation to the circulation changes is mostly related to ozone loss, indirectly caused by particles precipitating into the high latitude atmosphere within the wintertime polar vortex.

Precipitating particles are accelerated within the magnetosphere by processes, which gain energy from the solar wind. Such particles range from lower energy (∼100 eV to ∼10 keV) auroral (plasma sheet) particles to the more energetic particles of the ring current and radiation belts (∼10 keV to several MeV) [*Baumjohann and Treumann*, 1997]. Recurrent and persistent geomagnetic activity producing acceleration and precipitation of these particles are driven predominantly by high-speed solar wind streams [e.g., *Richardson and Cane*, 2012] whose occurrence maximizes during the declining phase of sunspot cycle [*Mursula et al.*, 2015]. Therefore, the usage of geomagnetic activity indices, such as the long-term *aa* index, as a proxy for low and medium energy particle precipitation is justified, since they mainly measure the variations of auroral electric currents, which are associated with particle precipitation up to tens of keV [e.g., *Hardy et al.*, 1985; *Østgaard et al.*, 2002; *Asikainen and Mursula*, 2014].

Low and medium energy particles penetrate mostly into the thermosphere and mesosphere, where they induce chemical reactions producing nitrogen oxides (NO_x) [*Sinnhuber et al.*, 2014; *Funke et al.*, 2014b] and hydrogen oxides (HO_x) [*Verronen et al.*, 2011; *Andersson et al.*, 2014]. These molecules can then act as catalysts in processes destroying ozone in the mesosphere [*Andersson et al.*, 2014]. During the polar night, in the absence of sunlight the lifetimes of NO_x molecules are long and with the large-scale downward motion in the middle atmosphere during winter, they can descend down to the stratosphere and cause significant ozone loss there too [*Randall et al.*, 2005; *Konopka et al.*, 2007; *Baumgaertner et al.*, 2011]. Ozone is the main factor controlling thermal structure of the stratosphere, as it absorbs solar UV (shortwave) radiation and also infrared (longwave) radiation from the Earth. Accordingly, reduction of ozone content in the high latitude stratosphere leads to changes in heating rates producing heating in the upper and cooling in the lower stratosphere through changes in longwave radiation and dynamical cooling [*Langematz et al.*, 2003]. This affects the overall circulation in the stratosphere through thermal wind balance. In particular the lower stratosphere cooling leads to acceleration of the polar vortex [*Baumgaertner et al.*, 2011]. Circulation changes in the stratosphere can propagate to the surface level and connect to the circulation in the Arctics, the North Atlantic region, and the North Pacific region [*Baldwin and Dunkerton*, 2001; *Kidston et al.*, 2015]. The polar vortex has an essential role in the northern annular mode (NAM) and North Atlantic Oscillation (NAO) patterns, which strongly control the winter climate conditions in the middle to high latitudes in the Northern Hemisphere [*Hurrell et al.*, 2003]. This indirect effect of precipitating particles is widely documented both by observations [see, e.g., *Seppälä et al.*, 2009, 2013; *Maliniemi et al.*, 2013; *Andersson et al.*, 2014] and by modeling results [see, e.g., *Baumgaertner et al.*, 2011; *Rozanov et al.*, 2005, 2012]. Moreover, we recently showed that only during the declining phase of the sunspot cycle the surface temperature pattern resembled the positive NAO phase temperature pattern, which supports the NAO relation to the solar cycle variation of energetic particles [*Maliniemi et al.*, 2014].

Another solar forcing to the polar vortex and tropospheric weather during winter is the solar UV radiation. It has been shown that the stronger UV radiation during solar maxima increases equatorial stratospheric ozone content [*Haigh*, 1994, 2007] and absorption of UV radiation, which enhances meridional temperature gradients, intensifying westerlies in the extratropics and leading to a stronger polar vortex and positive NAO [*Kodera*, 2002; *Kodera and Kuroda*, 2002; *Matthes et al.*, 2006]. This has been observed also in the summer [*Lee and Hameed*, 2007]. The solar total and spectral irradiances are typically in phase with the sunspot cycle peaking during solar maxima [*Lockwood and Fröhlich*, 2007]. Recently *Gray et al.* [2013], using sea level pressure observations also showed a positive NAO pattern lagging 2–4 years solar cycle maxima for time period 1870–2010, which they explained with the lagged ocean response to the solar UV increase [*Andrews et al.*, 2015]. It has also been proposed that the interplanetary magnetic field and solar wind variability can have more direct and temporally shorter pathway to the troposphere through modulation of the global atmospheric electric circuit [*Lam et al.*, 2013]. Evidence for this has been observed in summertime thunder storm rates, at least around Great Britain [*Scott et al.*, 2014; *Owens et al.*, 2014] and also in the Antarctic surface temperatures [*Francia et al.*, 2015]. However, the details of this mechanism, e.g., how global electric circuit changes lead to the observed meteorological responses, are not yet fully understood [*Lam et al.*, 2014].

The positive correlation between geomagnetic activity and wintertime NAO is clearly visible and significant in the latter half of the twentieth century [*Thejll et al.*, 2003; *Lukianova and Alekseev*, 2004; *Li et al.*, 2011]. *Palamara and Bryant* [2004] studied the correlation between geomagnetic *aa* index and NAM for individual months and observed (similarly as *Thejll et al.* [2003] slightly earlier) consistent positive correlation mainly in the winter months after 1950s. As many other studies, they did not consider any time difference between *aa* and NAM. However, the time lag between particle forcing, i.e., geomagnetic activity and surface signal may be important in winter due to the delay caused by NO_x descent from the mesosphere into the stratosphere [*Seppälä et al.*, 2009; *Funke et al.*, 2014a]. *Palamara and Bryant* [2004] also observed a stronger positive correlation between geomagnetic activity and NAM during the easterly phase of the quasi-biennial oscillation (QBO), which was later verified by others [*Bochníček and Hejda*, 2006; *Maliniemi et al.*, 2013]. All of these studies used QBO defined in the 30 hPa height. However, also somewhat opposing results have been obtained [e.g., *Lu et al.*, 2008b; *Seppälä et al.*, 2013], which show a larger positive polar vortex related to geomagnetic activity during westerly QBO, defined in 50 hPa height. The time period of all these studies related to the QBO modulation roughly coincide and is limited to the latter half of the twentieth century.

The effect of QBO on the polar vortex region is usually explained by the so called Holton-Tan mechanism, where the zonal wind zero line is pushed farther north during the easterly phase of the QBO, whence planetary waves are preferentially guided into the polar vortex region, depositing momentum and decelerating the vortex [*Holton and Tan*, 1980; *Baldwin et al.*, 2001]. This has been shown to have a nonstationary behavior [*Lu et al.*, 2008a, 2014] and also to be dependent on solar activity level [*Labitzke and van Loon*, 1988; *Naito and Hirota*, 1997; *Ruzmaikin and Feynman*, 2002]. QBO also affects the polar vortex region by enhancing the ascent rate in the tropics during easterly QBO [*Baldwin and Dunkerton*, 2001; *Flury et al.*, 2013]. This increases the meridional Brewer-Dobson circulation and enhances ozone levels at high latitudes especially in late winter and spring [*Li and Tung*, 2014].

In this study we aim to clarify these mutually conflicting results related to the Holton-Tan relationship and the long-term variability of the geomagnetic activity-NAM relation and its QBO modulation. We consider different phases of the winter (early winter versus late winter) and different time lags between geomagnetic activity

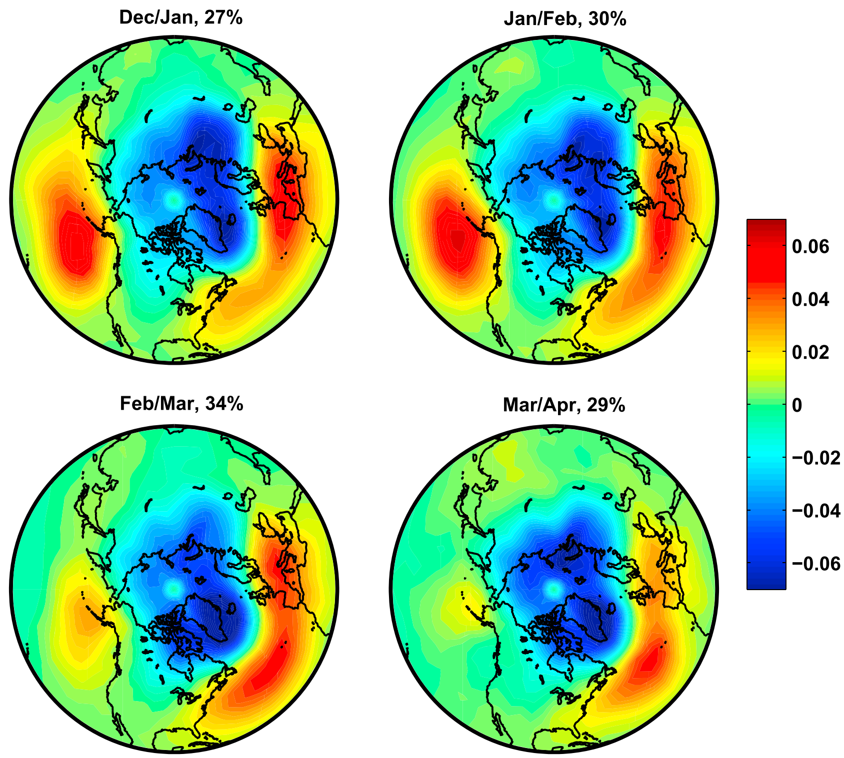

Figure 1. First EOFs of SLP data in four different winter months for years 1900–2013 (December/January) and 1901–2014 (January/February, February/March, and March/April). Percentages of the total variance explained by the first PC are shown in each case. The EOFs of different winter months have the same color scaling.

and NAM within the winter period to take into account the possible delay in NAM response, e.g., due to NO_x descent. We also consider QBO indices measured at the two commonly used altitudes (30 hPa and 50 hPa). The paper is organized as follows. In section 2 we explain the procedure of calculating the NAM pattern. In section 3 we will discuss the long-term correlation between geomagnetic activity and NAM, in section 4 the Holton-Tan relation and in section 5 the effect of geomagnetic activity and QBO on the NAM. Discussion of results is given in section 6 and the concluding remarks in section 7.

2. Northern Annular Mode of Sea Level Pressure and Surface Temperature

We used Hadley Center Sea level Pressure (SLP) Analysis 2 data and Goddard Institute for Space Studies (GISS) Surface Air Temperature (SAT) data to calculate the patterns related to the NAM. The Hadley Center SLP data are given in a 5°×5° latitude-longitude grid and GISS SAT data in a 2°×2° grid. In this analysis we only included the Northern Hemisphere data between latitudes 20 and 90°N. To construct the NAM pattern and the corresponding time series we used unrotated principal component analysis (PCA) over the selected mean winter seasons for the years 1900–2013. Before calculating the PCA we removed the long-term trend from both SLP and SAT data to guarantee that the patterns were not dominated or contaminated by long-term trends, which were especially notable in the temperature data (not shown). The trend removal was done as in *Maliniemi et al.* [2014], by applying a 31 year running LOWESS (locally weighted scatterplot smoothing from *Cleveland and Devlin* [1988]) to the data in each grid point before applying PCA. It is important to note that this non-linear trend removal enables us to study the correlation between *aa* and NAM at solar cycle time scales. In the PCA each grid point was weighted with the square root of cos(latitude) to take into account the area of the grid box on a spherical surface. To obtain winter time series in different phases of the winter we calculated four different time series corresponding to four different 2 month winter seasons: December/January, January/February, February/March, and March/April. The shorter 2 month winter definitions allow a better separation between the early and late winter than the more conventional 3 month winter definition.

The leading empirical orthogonal functions (EOFs) for SLP can be seen in Figure 1 and for SAT in Figure 2. First EOFs in both SLP and SAT are well separated from the second EOFs so that second PCs roughly explain 10–15%

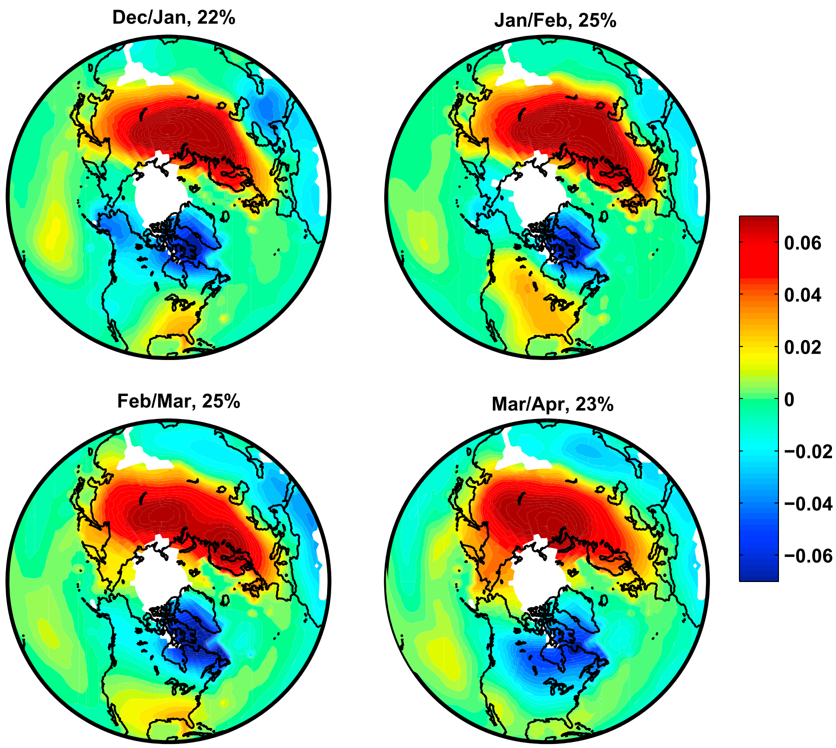

Figure 2. First EOFs of SAT data in four different winter months for years 1900–2013 (December/January) and 1901–2014 (January/February, February/March, and March/April). Percentages of the total variance explained by the first PC are shown in each case. The EOFs of different winter months have the same color scaling. White areas contain data gaps in the original data during 1900–2014 (mainly in the early twentieth century) and were excluded from the analysis.

of the total variance, whereas first PCs explain 20–30% of variance, as seen in Figures 1 and 2 where we have included the total variance explained by the first PC in each case. (The sign of the PC and the corresponding EOF is ambiguous in the PCA. In order to enable direct comparison between the different PCs, we ensured that each EOF and the corresponding PC have the same polarity, so that the positive value of the PC corresponds to the EOFs presented in Figures 1 and 2.) White areas in SAT EOFs represent areas where time series in the original data had gaps during the time period of 1900–2014 (mainly in the early twentieth century). These areas were excluded completely from the analysis.

In Figure 1 one can see the well-known NAM pattern more or less in all four winter months with negative SLP anomaly from Greenland to Barents Sea and positive anomalies from east coast of North America to Central/Eastern Europe and on the coast of West Canada and Alaska. There are notable differences between the different winter months so that the positive anomaly around Aleutian is weakening in the late winter compared to the early winter. Same is seen in the spatial extension of the positive anomaly in the North Atlantic which is somewhat smaller in the late winter. The negative anomaly at high latitudes is very consistent in all winter definitions. NAM patterns in SAT in Figure 2 also greatly resemble each other and the common pattern for NAO/NAM [*Hurrell et al.*, 2003] with main negative anomalies around Greenland and North Canada and strong positive anomalies over the entire Northern Eurasia. There are also weaker negative anomalies in Middle East and North Africa and weak positive anomalies in southeast of North America. Comparable to the SLP patterns the SAT patterns in late winter also show somewhat weaker anomalies than in early winter at least over Europe and Greenland, but the overall pattern remains quite similar in different winter definitions.

3. Long-Term Correlation Between *aa* Index and NAM

Let us study the correlation between geomagnetic activity and winter NAM on the surface. The long-running *aa* index of geomagnetic activity is taken as a rough proxy for energetic particle precipitation. For the comparison with the NAM indices of different winter seasons we calculated the mean *aa* over the early winter season, i.e., December/January, unlike, e.g., *Palamara and Bryant* [2004] who used the same month for *aa* and

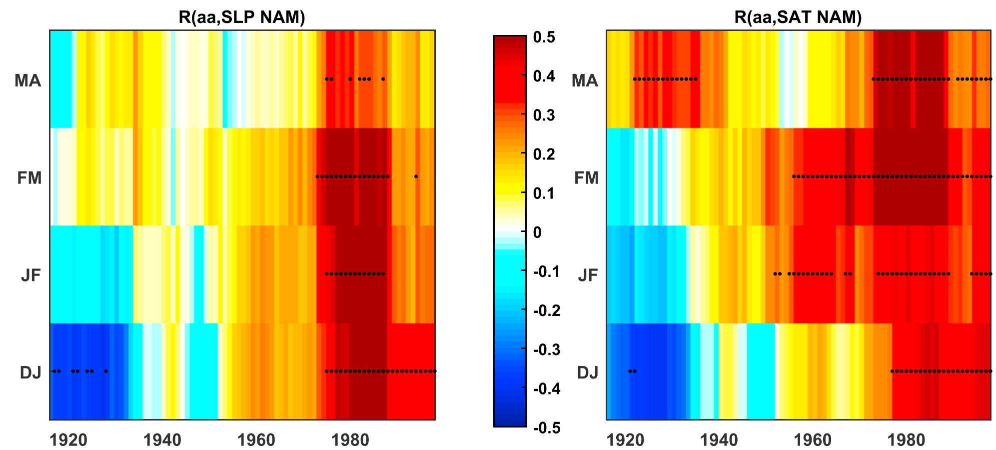

Figure 3. Color plot of correlation coefficient *R* between *aa* index (December and January) and first PC of (left) SLP and (right) SAT in four different winter definitions (DJ December/January, JF January/February, etc.). Black dots indicate the significant correlation with *p* value less than 0.1.

NAM index. This choice was made in order to study the possible delay between geomagnetic forcing and surface signal associated with, e.g., the NO_x descent [*Seppälä et al.*, 2009; *Funke et al.*, 2014a]. *Seppälä et al.* [2013] have noted that geomagnetic impacts on the atmosphere after January are not likely to have any long-term effects. The long-term trend was removed from the *aa* index similarly as from the SLP and SAT data.

To study the temporal variation of the relationship between *aa* and NAM (both SLP and SAT) the correlation coefficient between the two was calculated in 31 year windows (±15 years around the central year) sliding forward in time in 1 year steps. Assigning the correlation coefficient to the center of the time window yields the annually varying correlation for the time period 1916–1999. Statistical significance of the correlation coefficient in each window was estimated with a Monte-Carlo simulation. In this simulation we generated surrogate time series of *aa* and NAM by phase randomization of the observed data series, which preserves the statistical properties of the time series, including the autocorrelation function (for more details, see *Maliniemi et al.* [2013]). We then computed the correlation coefficient of these surrogate series and repeated this process 3000 times for each 31 year window in order to produce a histogram of correlation coefficients. This histogram was then used to estimate the probability (*p* value) of obtaining the correlation coefficient of the original data by chance in a case of no correlation.

Figure 3 shows the results of the correlation analysis between *aa* and NAM (SLP on the left and SAT on the right). The different winter seasons for the NAM indices have been indicated on the vertical axis (DJ is December/January etc.), so that the time lag between the *aa* and NAM within the winter increases along the vertical axis. The statistically significant correlations (chosen as $p < 0.1$) are indicated in the plots by black dots. One can see that, since 1960s/1970s significant positive correlation existed for both SLP and SAT over the whole winter, which is consistent with the earlier studies [e.g., *Thejll et al.*, 2003; *Lukianova and Alekseev*, 2004]. However, positive correlation in the late winter extends much further back in time and is also significant in the SAT case in early twentieth century. Even though the statistical significance is poor for SLP NAM in early twentieth century, these observations indicate that the response of *aa* in NAM has been different in early and late winter.

4. Holton-Tan Mechanism in Surface NAM

The Holton-Tan relation states that the stratospheric polar vortex is weaker during easterly QBO and stronger during westerly QBO [*Holton and Tan*, 1980; *Baldwin and Dunkerton*, 2001]. To see whether this relation is also seen on the surface throughout the twentieth century we study the correlation of QBO and NAM similarly as was done above (Figure 3) for *aa* and NAM. We use here the long-term reconstruction of QBO at 30 hPa and 50 hPa, which extend to the beginning of twentieth century [*Brönnimann et al.*, 2007]. One must note here that the QBO reconstruction is obtained from relatively sparse data sources in the early twentieth century and thus includes a rather large uncertainty before 1950s. On the other hand *Brönnimann et al.* [2007] state that the reconstruction captures relatively well the maximum phases of the QBO already since about 1910, as confirmed by the historical balloon and ozone measurements. Keeping this in mind we can use the

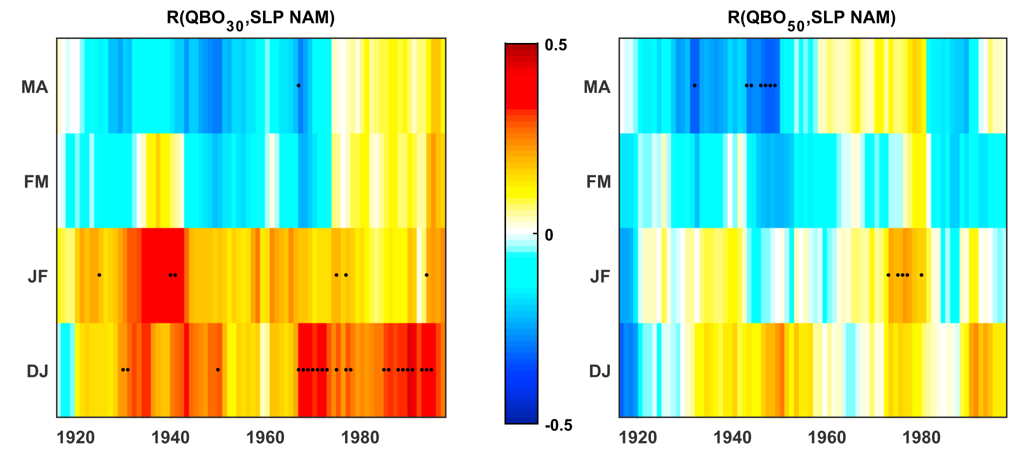

Figure 4. Color plot of correlation coefficient R between QBO index ((left) 30 hPa and (right) 50 hPa) and first PC of SLP in four different winter definitions (DJ December/January, JF January/February, etc.). Black dots indicate the significant correlation with *p* value less than 0.1.

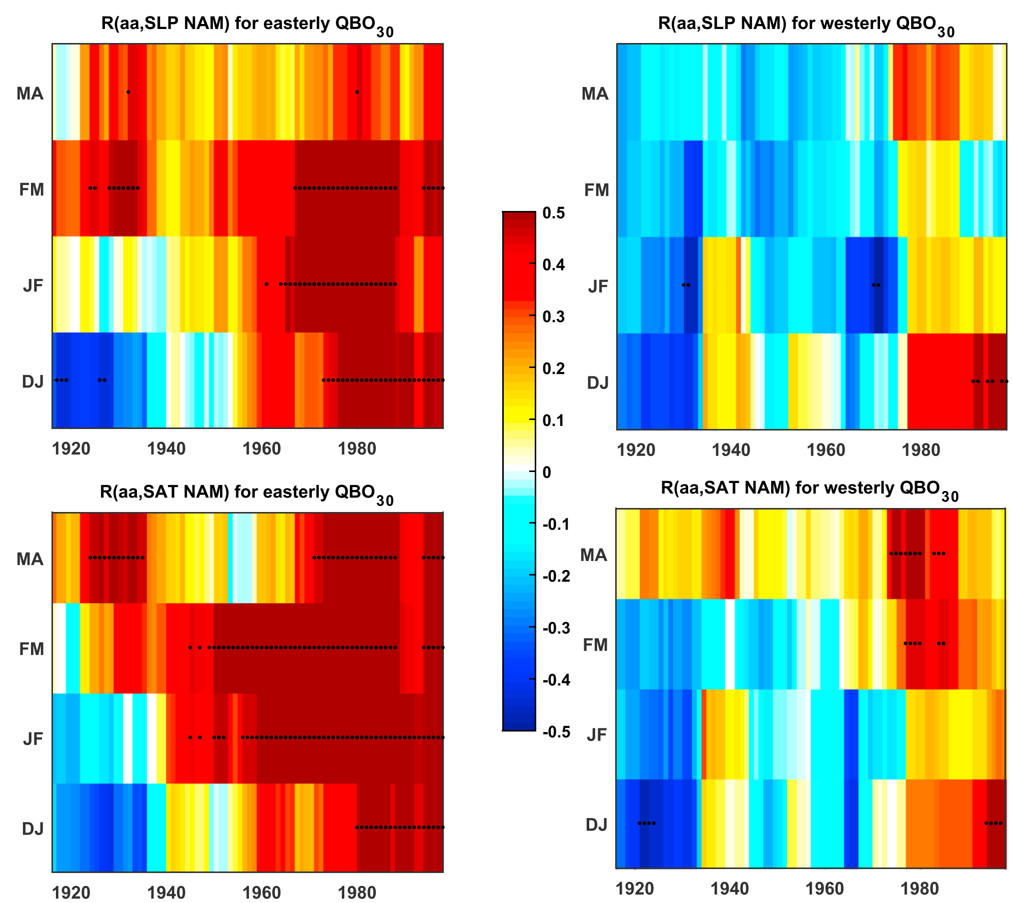

Figure 5. Color plot of correlation coefficient *R* between *aa* index (December and January) and first PC of (top row) SLP and (bottom row) SAT in four different winter definitions (DJ December/January, JF January/February, etc.) during easterly QBO (left column) and westerly QBO (right column) in 30 hPa. Black dots indicate the significant correlation with *p* value less than 0.1.

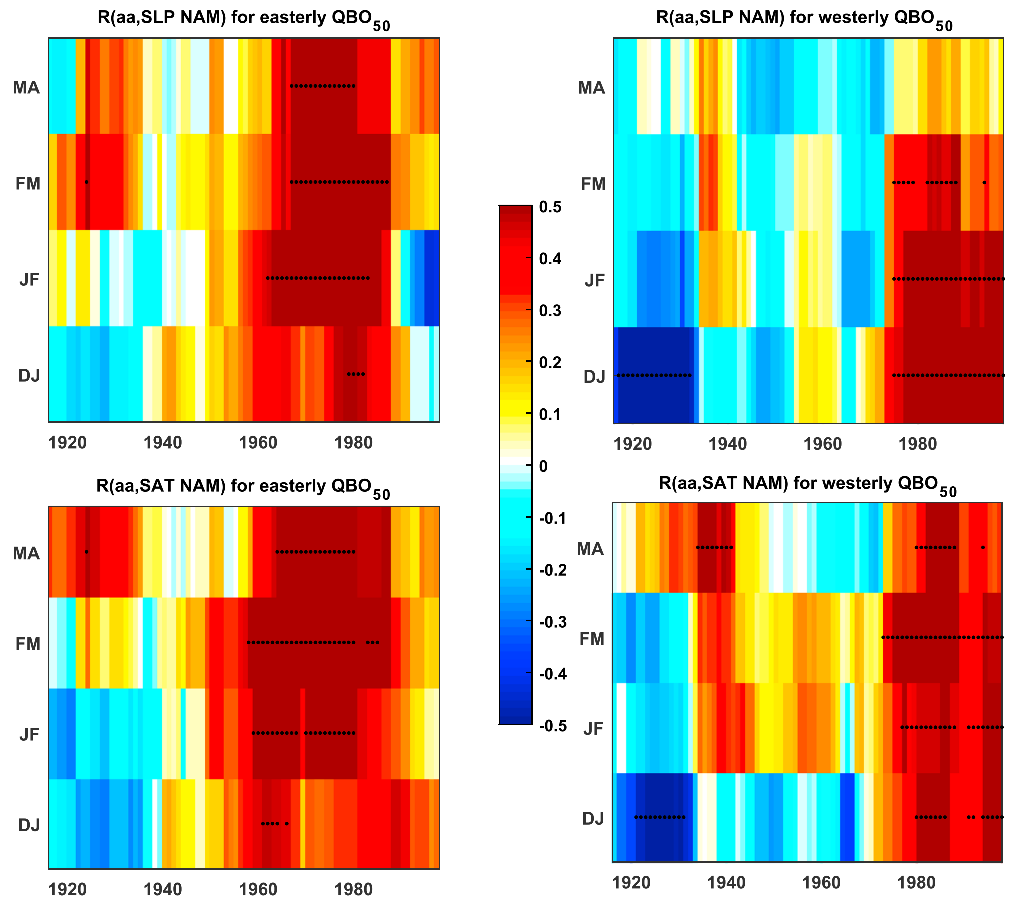

Figure 6. Same as Figure 5 but with QBO 50 hPa.

reconstruction as a rough estimate of the QBO variability over the whole 1900s. From here on we refer the QBO indices at the two pressure levels as QBO_{30} and QBO_{50}.

We calculated the winter average QBOs for the same four 2 month winter seasons as for the NAM above. The temporally varying correlation and statistical significance testing was then done in the same way as for *aa* and NAM. For simplicity we only discuss the correlation results obtained with SLP NAM index, since the results for SAT based NAM were essentially similar. Correlation between QBO and NAM is shown in Figure 4, where the left side shows results for QBO_{30} and right side for QBO_{50}. One can see that there is a positive relation between QBO_{30} and NAM in the early winter, but not in the late winter during the entire time period depicted. For the QBO_{50} the overall structure is similar but with much weaker positive correlation in the early winter. Significant correlation is only obtained for early winter and mostly only for QBO_{30}. Earlier results have also indicated that the Holton-Tan relation is on average stronger during early winter than late winter [*Lu et al.*, 2008a, 2014]. Our results clearly indicate that the QBO_{30} better represents the Holton-Tan relation for surface circulation.

5. Relation Between *aa*, NAM, and QBO

Most earlier studies have indicated that the relation between geomagnetic activity/solar wind and NAM/NAO is stronger during easterly QBO [*Palamara and Bryant*, 2004; *Bochníček and Hejda*, 2006; *Maliniemi et al.*, 2013]. However, *Seppälä et al.* [2013] and *Lu et al.* [2008b] have found that geomagnetic activity affects the stratosphere most efficiently during westerly QBO. Some of the apparent contradictions between different studies may come from the differing time coverages and the usage of QBO indices at different heights. In order to elucidate the effect of QBO we wanted to see if there is any difference in the results depending on which QBO is used. For this we calculated the correlation between *aa* and NAM (both SLP and SAT) during easterly (negative) and westerly (positive) QBO phase. The calculation was done separately for QBO_{30} and QBO_{50}.

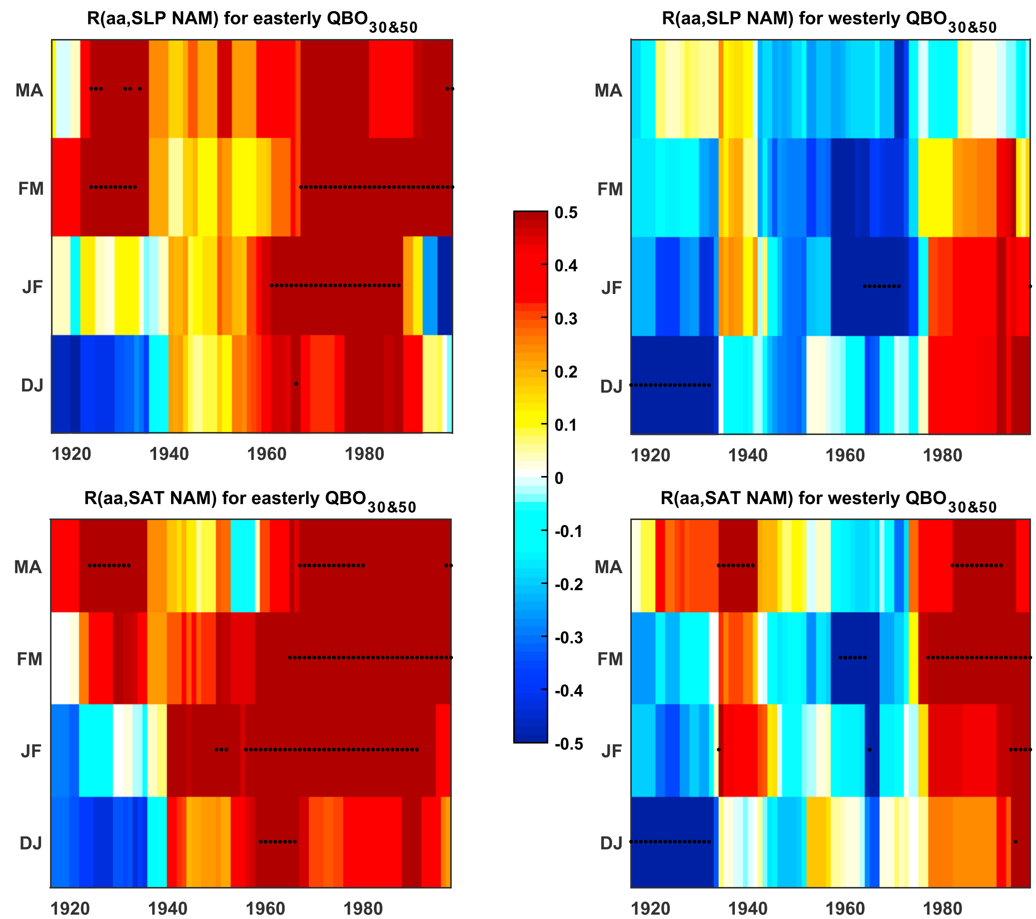

Figure 7. Same as Figure 6 but with both QBO 30 and 50 hPa considered simultaneously.

Figures 5 and 6 show the correlation between *aa* index and SLP/SAT based NAM indices separately for the two phases of QBO_{30} and QBO_{50}, respectively. One can see that the easterly QBO_{30} shows a similar overall structure to that in Figure 3 but with stronger and significant positive correlation in late winter also in the early twentieth century. For westerly QBO_{30} the correlation is mostly negative but has minor statistical significance. After about 1980 the correlations even for westerly QBO_{30} phase are mostly positive but much weaker than for the easterly QBO_{30} phase and mostly statistically insignificant. The strong QBO_{30} dependence of the NAM/*aa* correlation is also in agreement with our earlier results for the recent decades [*Maliniemi et al.*, 2013]. (Note that after separating the data into the two QBO phases, the autocorrelation in the resulting unevenly sampled time series of *aa* and NAM indices becomes negligibly small and can thus be ignored when estimating the statistical significance. Accordingly, the *p* values in Figures 5 and 6 were computed by the conventional *t* test.)

Comparison of results for QBO_{30} (Figure 5) and QBO_{50} (Figure 6) shows a roughly similar overall structure for both QBO heights. However, some significant differences are evident. First, the correlation is significantly positive during the recent few decades not only in easterly QBO_{30} but also in the westerly QBO_{50}. This is consistent with results obtained earlier by *Seppälä et al.* [2013] who found a stronger polar vortex during high geomagnetic activity in westerly QBO_{50} than easterly QBO_{50} including data from 1957 to 2008. Moreover, our results are also consistent with the earlier results by *Palamara and Bryant* [2004] who found better correlation between *aa* and NAM during easterly QBO_{30} than during westerly QBO_{30} for time period of 1965–1997. Notable is that the QBO modulation at both heights is less important in recent decades since about 1980, where all four cases (easterly QBO_{30}/westerly QBO_{30} and easterly QBO_{50}/westerly QBO_{50}) show positive correlation, though most significantly in easterly QBO_{30} and westerly QBO_{50}. On the other hand considering the entire twentieth century the overall positive correlation between *aa* and NAM is predominantly observed only during the easterly QBO phase, especially in QBO_{30} and to some extent in QBO_{50}. However, there seems to be clear difference again between early and late winter (similarly as in Figure 3) so that in the early twentieth century significant positive NAM response was observed only in late winter (FM and MA) during easterly QBO, while since 1950s the response has been increasingly observed throughout the whole winter. Another clear difference between the two QBO heights is that the QBO_{30} more clearly separates the correlation pattern between the two QBO phases: significant positive correlation for easterly QBO and weakly negative, barely significant correlation for westerly QBO. For QBO_{50} the difference between the two QBO phases is smaller.

We further tested the effect of QBO separation by requiring that both QBO_{30} and QBO_{50} to be in the same phase simultaneously. The results of this separation for correlations between SLP/SAT NAM and *aa* are shown in Figure 7. It is seen that the easterly QBO phase mostly reproduces (and slightly expanses) the correlation pattern of the easterly QBO_{30}, while the westerly QBO phase reproduces the correlations found for the westerly QBO_{50} in the last decades. Accordingly, when the whole stratosphere is in the westerly QBO phase, the effect of geomagnetic activity on NAM is significant and positive only in the last few decades. If it is in the easterly phase, the effect is significant and positive over the majority of the century either simultaneously or with a delay of a couple of months. We also note that in each of the QBO separated cases presented above we find that SLP and SAT based NAM indices behave quite similarly. This further gives us confidence that the SLP and SAT principal components are representations of the same circulation pattern.

6. Discussion

Our results support the idea that geomagnetic activity and the northern annular mode correlate positively. Unlike all earlier studies we find that positive correlation is present not only during recent decades but also in the early twentieth century, if the timing of surface NAM signal during the winter season is allowed to vary and the QBO phase is taken into account. We find that in the early twentieth century the positive correlation between NAM and geomagnetic activity appears only in the late winter (FM/MA) when QBO_{30} is in easterly phase. During the recent decades since about 1960s the positive correlation of NAM and geomagnetic activity is seen already earlier in the winter (beginning from DJ). Overall this correlation in the easterly QBO phase is more evident when the QBO_{30} rather than QBO_{50} is used. We also verify that the Holton-Tan relation is valid throughout the century but much more systematically for QBO_{30} than for QBO_{50}. Moreover, we find that the Holton-Tan relation only applies in the early winter (see Figure 4).

The Holton-Tan relation is considered to arise due to the northward shift of the zero line of zonal wind during easterly QBO, whence planetary waves are directed northward, thus disturbing the polar vortex [*Baldwin et al.*, 2001] and leading to a more negative surface NAM. However, several studies have shown that solar activity can affect this relation [e.g., *Labitzke and van Loon*, 1988, 2000; *Naito and Hirota*, 1997; *Ruzmaikin and Feynman*, 2002]. *Labitzke and van Loon* [1988] showed that polar stratosphere was warmer (colder), i.e., the vortex was weaker (stronger) during easterly (westerly) QBO and weak solar activity, but during high solar activity the relation was reversed. In addition, *Naito and Hirota* [1997] showed that solar activity modified the Holton-Tan mechanism so that it only works during low solar activity. Recently, it has been shown that the strengthening of the polar vortex since 1970s has led to a somewhat weaker Holton-Tan mechanism when QBO_{50} was considered [*Lu et al.*, 2014].

These results suggest that there are other forcings (like solar or geomagnetic activity) that affect the polar vortex strength and the Holton-Tan relation. To test whether the relationship between QBO_{30} and surface NAM depicted in Figure 4 is affected by geomagnetic activity we calculated the mean value of SLP NAM in four cases: QBO_{30} east/low *aa*, QBO_{30} west/low *aa*, QBO_{30} east/high *aa* and QBO_{30} west/high *aa*. NAM and *aa* were standardized over the whole time period before the grouping. (QBO was not standardized, since it obtains larger amplitudes in easterly phase. As discussed above, the trend is removed from *aa* and NAM before the analysis.) We also calculated the significance levels for the differences between each case using a two-sample *t* test. (We note that the temporal autocorrelation of winter mean NAM index after trend removal is rather low (<0.12) with lags 1–10 in both early (DJ) and late (FM) winter and thus can be neglected when calculating significance levels).

Figure 8 shows the average NAM values for the four cases and the *p* values of the differences between each case (indicated by the arrows) during early winter of 1900–2013. Holton-Tan relation is found to be significant only for the low *aa* case. Figure 8 also clearly shows that the correlation between *aa* and NAM during easterly QBO_{30} results from the low value of NAM in QBOe/low *aa* case, not so much from the weakly positive value of NAM in QBOe/high *aa* case. For westerly QBO_{30} there is an insignificant overall correlation between *aa* and NAM, in agreement with results discussed above.

The largest NAM is obtained for QBOw/high *aa* when planetary wave effects are weak and particle precipitation forcing is strong, while the lowest value of NAM corresponds to QBOe/low *aa*, when the planetary wave forcing is large and particle precipitation forcing small. It also seems that the difference in average NAM between low *aa* and high *aa* is about twice as large in easterly QBO_{30} than in westerly QBO_{30}, which is again an indication of better *aa*/NAM correlation in easterly QBO_{30}. During easterly QBO_{30}, enhanced particle precipitation makes the vortex strong enough to resist the effect of planetary waves. In westerly QBO_{30}, when the planetary wave effect on the polar vortex is small, the enhancement of the vortex due to particle precipitation would have a smaller relative effect.

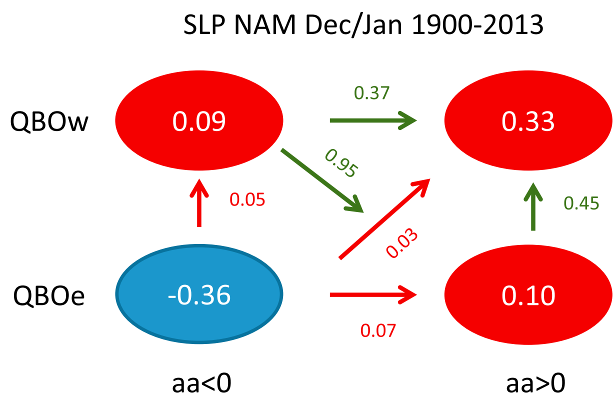

Figure 8. Mean NAM values in each of the four cases (QBO_{30} east/low *aa*, QBO_{30} west/low *aa*, QBO_{30} east/high *aa*, and QBO_{30} west/high *aa*) during December/January 1900–2013. NAM and *aa* are standardized over the whole time period. Significance of the difference between each case is shown with the arrows (red arrows represents *p* values less than 0.1 and green arrows *p* values larger than 0.1).

A similar analysis for the late winter yields some interesting differences (see Figure 9). During low *aa* the difference between easterly and westerly QBO_{30} is not as large (in fact statistically insignificant) as in the early winter. This is an indication that the Holton-Tan mechanism is weaker in late winter (as suggested, e.g., by *Lu et al.* [2008a, 2014]). This is also seen in Figure 4, where no correlation between QBO and NAM is observed in FM/MA. On the other hand, Figure 9 shows that there is quite a clear and statistically significant difference between the QBO_{30} phases during high *aa* values, so that in easterly QBO_{30} phase the high *aa* values correspond to strongly positive NAM values, but in the westerly QBO phase they yield a weakly negative NAM. This shows that in the late winter and high geomagnetic activity there is actually an anti-Holton-Tan relationship, which further reduces the overall Holton-Tan relationship in the late winter. There is also highly significant difference between high and low *aa* during easterly QBO_{30} (in agreement with Figure 5, QBO easterly), which now mainly results from the high value during QBOe/high *aa* case.

Based on these findings we propose that the late winter large *aa* anti-Holton-Tan relation is likely due to the effect that the QBO phase has on the Brewer-Dobson circulation [*Baldwin and Dunkerton*, 2001]. It has been shown that the Brewer-Dobson circulation in the tropics is enhanced during the easterly QBO phase [see, e.g., *Flury et al.*, 2013]. Enhanced ascent of air in the tropics enhances ozone levels in the high equatorial and midlatitude stratosphere during easterly QBO and late winter [see, e.g., *Randel and Cobb*, 1994, Figure 11; *Baldwin and Dunkerton*, 2001, Figure 23]. It also enhances ozone content in the high latitudes especially during late winter [*Li and Tung*, 2014]. *Bowman* [1989] showed that the QBO strongly anticorrelates with the amount of ozone in polar regions between 70 and 90°N in late winter (February–April). Ozone loss inside the polar vortex catalyzed by NO_x and HO_x is expected to be proportional not only to the concentration of these molecules but also to the ozone content. Thus, the larger ozone content during easterly QBO would lead to a larger ozone loss in response to a given amount of NO_x/HO_x (or geomagnetic activity/particle precipitation level). In late winter the larger ozone loss inside the polar vortex and the larger amount of ozone outside the polar vortex in easterly QBO would

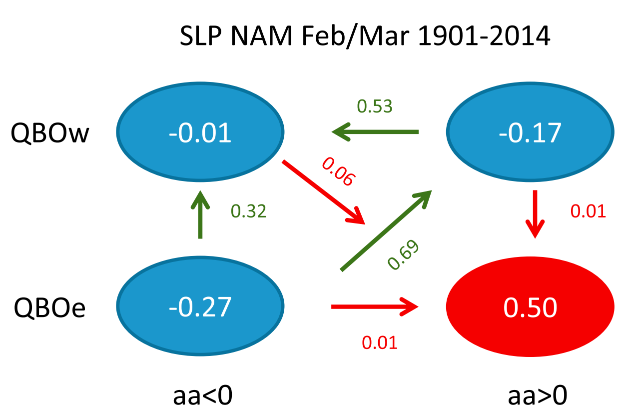

Figure 9. Same as Figure 8 but for late winter (February/March) 1901–2014.

lead to a larger temperature gradient between polar vortex region and midlatitudes/low latitudes during high geomagnetic/particle activity, thus increasing westerlies in the extratropics. This is seen as a stronger vortex in late winter in high geomagnetic activity times for easterly QBO phase, which would translate to a more positive surface NAM at these times.

7. Conclusions

We have studied here the QBO-modulated correlation between geomagnetic activity (*aa* index) and the northern annular mode, as represented by the first principal component of sea level pressure and surface temperature. We considered their relationship for two commonly used QBO heights, 30 hPa and 50 hPa, as well as combination of these two. In addition, we studied how this relation is observed in different phases of the winter. Using QBO at 30 hPa we confirmed the result of *Palamara and Bryant* [2004] that average correlation in 1965–1997 is stronger (and positive) during easterly QBO_{30} than westerly QBO_{30}. We also showed that for the last few decades QBO modulation is less important and that the positive correlation is stronger during westerly QBO_{50} than easterly QBO_{50}, in agreement with the results of *Seppälä et al.* [2013]. We also find that QBO_{30} better distinguishes the differences in the *aa* index-NAM relation between the two QBO phases: significantly positive correlation during easterly QBO_{30} and weak, mainly insignificant negative correlation during westerly QBO_{30} during most of the century. The positive correlation during easterly QBO_{30} shifts to late winter toward the early part of the twentieth century.

We have shown here that the Holton-Tan relation is overall more systematically valid for QBO_{30} than for QBO_{50} and that it is only observed in early winter. We found that in the early winter the Holton-Tan relation is significant only during weak geomagnetic activity and not during strong activity. This is due to the fact that the mean value of NAM is strongly negative for weak *aa* index and easterly QBO_{30} phase, while it is positive for the other three combinations. However, in late winter there is no significant Holton-Tan relation during weak geomagnetic activity. Instead, there is significant anti-Holton-Tan relation during strong geomagnetic activity. This is due to the fact that the average NAM value is much larger (positive) for strong *aa* index and easterly QBO_{30} than for the other three combinations.

Difference in NAM between strong and weak geomagnetic activity in early winter is significant and about twice as large in easterly QBO_{30} than in westerly QBO_{30}. This is probably because the efficiency of planetary wave drag on the polar vortex is larger, when the vortex is weaker (easterly QBO). As a result, in easterly QBO changes in vortex strength related to ozone loss affect the deposition of planetary wave momentum relatively more efficiently than in westerly QBO, when the vortex is stronger due to less effective planetary wave drag. Difference in NAM between strong and weak geomagnetic activity in late winter is also significant and much larger during easterly QBO than in westerly QBO. We propose that this late winter effect is possibly through enhanced Brewer-Dobson circulation during easterly QBO. Intensified Brewer-Dobson circulation enhances ozone content in the high latitude stratosphere in late winter. The larger ozone content is expected to result in larger ozone loss as a response to energetic particle precipitation inside of the polar vortex, thus enhancing temperature gradient between polar vortex region and midlatitudes. This would lead to a larger NAM response to geomagnetic activity (particle precipitation) variations during easterly QBO.

These results give new evidence of a possible mechanism behind the QBO modulation of *aa* index/NAM relationship, but additional research is needed to verify the stratospheric feedback mechanism. Our results not only highlight the systematic response of NAM to particle precipitation during the entire twentieth century but also show importance of considering atmospheric preconditioning when studying the effect of an external driver, e.g., geomagnetic activity on the NAM.

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