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# NOTES AND CORRESPONDENCE Effect of QBO and ENSO on the Solar Cycle Modulation of

## Winter North Atlantic Oscillation

## Yuhji KURODA

Meteorological Research Institute, Tsukuba, Japan

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## Abstract

The effect of the Quasi-Biennial Oscillation (QBO) and the El Niño Southern Oscillation (ENSO) on the 11-year solar cycle modulation of the winter-mean North Atlantic Oscillation (NAO) is examined through analysis of observational data from 1958 to 2000. It is found that the solar cycle modulation of the NAO is more strongly enhanced in the westerly phase of the 50-hPa QBO wind and the cold phase of ENSO, although separation of these effects is statistically difficult. On these phases, the signal of the winter-mean NAO extends more to the upper stratosphere and summer-AO reappears more strongly in high solar years, whereas the signal is weaker throughout in low solar years.

## 1. Introduction

The effect of sun on climate has been debated for a long time. With the accumulation of observational data including satellite data and improved qualities of the general circulation model, however, recent study of solar cycle effects on climate becomes one of the most important key problems to understand climate system. Estimation of such natural effects on climate is especially important to evaluate human impact on present climate and future prediction.

Satellite observation shows that the total energy flux from sun varies only about 0.1%, but it reaches several tenths of percent in short ultra-violet range, with the 11-year solar cycle (Rottman 1988; Lean et al. 1997). Such large variation in the ultra-violet region should have a large impact on the temperature (Hood et al.

1993; McCormack and Hood 1996) and ozone (e.g., Soukharev and Hood 2006) in the stratosphere. A large effect on the stratosphere will also have an important impact on the troposphere through stratosphere-troposphere coupling. In fact, Kodera (2002, 2003) and Ogi et al. (2003) found that the winter-mean North Atlantic Oscillation (NAO), which is known to have a large connection with the stratospheric variability (Ambaum and Hoskins 2002), is largely modified according to the phase of the solar cycle. They found that the winter-mean NAO signal extends to the upper stratosphere and reappears in summer in high solar (HS) years, whereas it is a local pattern and disappears very quickly in low solar (LS) years.

For the studies of solar cycle modulation of the NAO in Kodera (2002, 2003) and Ogi et al. (2003), other external forcings in climate, such as the QBO, ENSO and volcanic eruption, were not considered. However, previous studies indicate that the solar influence on climate is much affected by these phenomena (e.g., Labitzke and van Loon 1999). So it will be interesting to examine whether the other external effects

Corresponding author: Yuhji Kuroda, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan. E-mail: kuroda@mri-jma.go.jp

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890

such as the QBO and ENSO affect the solar cycle modulation of the NAO. The purpose of the present study is to examine the role of the QBO and ENSO on the solar cycle modulation of the winter-mean NAO.

## 2. Data and analysis method

The meteorological data we used in this study is from the 40-year reanalysis data of the European Centre of Medium-range Weather Forecasts (ERA40) (Uppala et al. 2005). We used 43 years of data from 1958 to 2000. In all analyses monthly-mean data have been used.

The NAO index used in the present study is the same as that used in Kodera (2002, 2003) and Ogi et al. (2003). It is the difference in the normalized monthly mean sea level pressure (SLP) between Lisbon and Stykkisholmur as calculated in Hurrell (1996). In this study, we used a winter-mean NAO index as the average from December to February (DJF). Solar cycle is classified by the December to March (DJFM) mean 10.7 cm solar radio flux. If DJFM-mean solar radio flux of a year is stronger (weaker) than the average, the year is categorized as a HS (LS) year. Similarly, phase of QBO is classified according to DJFM-mean zonal wind at 50hPa level on the equator. If DJFM-mean wind is westerly (easterly), the year is categorized as a QBO-west (east) year. Phase of ENSO is classified according to anomalous sea surface temperature (SST) of Nino 3 area in a similar manner. Here SST is adopted from HadISST (Rayner et al. 2003) and SST anomaly is defined from a departure from the "present climate" as an average from 1961 to 1990. These years for the present climate are used following to the convention of WMO. If DJFM-mean Nino 3 SST is warmer (colder) than normal, the year is categorized as a warm (cold) year.

These indices are shown in Fig. 1. Here the solid circle in the figure indicates years of positive index, whereas the open circle indicates negative index years. Here years correspond to the months of January. Numbers of years as well as the years used in the calculations are summarized in Table 1.

Although ERA40 data is available from the surface to 1 hPa, we have restricted our analysis to the more reliable region from the surface to 10-hPa.

Most of the figures in this paper present cor-



Fig. 1. Time coefficients of winter-mean NAO index (1<sup>st</sup> row), standardized F10.7 index (2<sup>nd</sup> row), QBO wind at 50hPa level (3<sup>rd</sup> row), and Nino3 sea surface temperature anomaly (4<sup>th</sup> row) used in the present study. Black solid (open) circle from 2<sup>nd</sup> to 4<sup>th</sup> panels indicates year whose time coefficient is positive (negative).

relation with the DJF mean NAO index. This means that the figures are relative to a 'positive change' in the DJF mean NAO index.

## 3. Results

Figure 2 indicates the correlation of the DJFmean zonal-mean zonal wind and SLP associated with the DJF-mean NAO index, calculated separately with various phases of the solar cycle, QBO, and ENSO. Except for the panel with all winters shown in the leftmost panel, the number of data used in the calculation is approximately about half of the original one. As the 98% (93%) level of statistical significance corresponds to a correlation of 0.5 (0.4) for 21 data, we have shaded the area greater than 0.4 and contoured greater than 0.5 with a step of 0.1.

It can be seen that the winter-mean NAO signal is largely modified according to the solar cycle; it extends to the upper stratosphere and the surface signal becomes more hemispheric in HS years, whereas it is a tropospheric local pattern in LS years, as is shown by Kodera (2002, 2003). In the case of modulation with the QBO-wind, it can be seen that the NAO signal becomes more hemispheric and extends to

December 2	20	07
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#### Y. KURODA

Table 1. Number of years used for the calculation in this study. Numbers in the bracket indicate years used for the calculation. Years correspond to the months of January.

HS 19 West 11 East 8 Warm 10 Cold 9	(59,60,67,68,69,70,71,79,80,81,82,83,89,90,91,92,93,99,00) (60,67,68,70,79,81,83,89,91,93,00) (59,69,71,80,82,90,92,99) (59,69,70,79,80,82,83,91,92,93) (60,67,68,71,81,89,90,99,00)	
	(61,69,69,66,71,90,50,50,50,70,72,72,72,72,94,95,96,97,98,04,05,06,07,08)	
West 13	(62,64,65,72,74,76,84,86,87,88,94,96,98)	
East 10	(61.63.66.73.75.77.78.85.95.97)	
Warm 9	(64,66,73,77,78,87,88,95,98)	
Cold 14	(61, 62, 63, 65, 72, 74, 75, 76, 84, 85, 86, 94, 96, 97)	
West 24	(60, 62, 64, 65, 67, 68, 70, 72, 74, 76, 79, 81, 83, 84, 86, 87, 88, 89, 91, 93, 94, 96, 98, 00)	
East 18	(59, 61, 63, 66, 69, 71, 73, 75, 77, 78, 80, 82, 85, 90, 92, 95, 97, 99)	
Warm 19	(59, 64, 66, 69, 70, 73, 77, 78, 79, 80, 82, 83, 87, 88, 91, 92, 93, 95, 98)	
Cold 23	(60, 61, 62, 63, 65, 67, 68, 71, 72, 74, 75, 76, 81, 84, 85, 86, 89, 90, 94, 96, 97, 99, 00)	



Fig. 2. Correlation coefficients between December-February mean NAO index and the December-February mean zonal-mean zonal wind (upper panels) and sea level pressure (lower panels) at each grid point for the period of 1958-2000. Each panel shows, from left to right, the correlation calculated from all data, high solar, low solar, QBO west, QBO east, ENSO warm, and ENSO cold years, respectively. The contour interval is 0.1, and contours are drawn for absolute values greater than or equal to 0.5 and for zero. Shading is applied to regions where the absolute value of the correlation is greater than 0.4. Dashed lines indicate negative values.

upper altitude in the east years, but it is a tropospheric local one in the west years. In the case of modulation with the ENSO cycle, the NAO signal extends more to upper altitude in the warm phase, but extension is small in the cold phase as is shown by Kodera (2004). In the case of the warm phase, meridional tripole structure in the zonal wind is also prominent. It should be noted that the Pacific side has the same polarity as the Atlantic one in the cold phase, but it is opposite in the warm phase in the SLP signal (Quadrelli and Wallace 2002). It is interesting to note that in all cases the polar center of the SLP signal extends to a much wider region in correspondence with the vertically higher extension of the zonal wind signal.

For the influence of the solar cycle, Ogi et al. (2003) found that the temporal signal is also largely modified according to the solar cycle. Figure 3 compared the correlation of twomonth mean zonal wind from December-



Fig. 3. Same as Fig. 2, except showing two-month mean zonal wind from December-Janauary to August-September. Each panel shows the correlation calculated from high solar years (upper panels) and low solar years (lower panels), respectively.

January (DJ) to August–September (AS) with the DJF-mean NAO for the HS and LS years. It can be seen that the AO-like signal reappears in summer only in HS years, except for a large vertical extension in winter.

It is interesting to examine the NAO modulation according solely to the QBO and ENSO cycle for the first step to examine compound effects of the QBO (or the ENSO) and the solar cycle. Figure 4 shows temporal variation of correlation of the zonal wind with the wintermean NAO index according to the QBO and ENSO cycle. In the case of the modulation by the QBO (upper panels), it can be seen that the signal is almost absent in the case of the west phase, except for winter. In the case of east phase, however, poleward propagation of meridional dipole signal from DJ to AM is prominent in the troposphere. Slow downward signal in the tropical stratosphere is also present. In the case of the modulation by the ENSO (lower panels), the NAO signal is very weak and the signal is present almost only in winter in the cold phase. In contrast, the signal is rather strong in the case of the warm phase. Poleward propagation of the meridional dipole signal is prominent in the troposphere with larger vertical extension toward the stratosphere. The signal becomes especially very strong and extends to the upper stratosphere in August (not shown). The feature is very similar to the typical summer Arctic Oscillation (S-AO) (Ogi et al. 2004).

To examine the effect of the QBO on the solar cycle modulation of the winter-mean NAO, we further separated each solar cycle year into QBO-west or east years. By this operation, the sample size of each group becomes about 10 (Table 1). With this size it is still possible to perform statistical discussion, although it will be not enough. Figure 5 shows the comparison of the solar cycle modulation of the NAO on the condition of QBO west (upper panels) and east phases (lower panels). As the 93% (85%) level of statistical significance corresponds to a correlation of 0.6 (0.5) for 10 data, we have shaded the area greater than 0.5 and contoured greater than 0.6 with a step of 0.1.

In the case of the west phase of the QBO, solar cycle modulation of the NAO is very similar to that observed without QBO separation (Ogi et al. 2003) but it is more prominent. In fact, the zonal wind signal extends more strongly to the upper stratosphere in winter and a strong AO-like signal reappears in summer (JJ to AS) in HS/west years, whereas the signal is very weak throughout, even in winter, in LS/west years. A signal with slow downward and poleward propagation also exists in the subtropical upper stratosphere in HS/west years, which should be closely related to the QBO signal.

In the case of east phase of the QBO, wintermean NAO signal extends more in HS/east than LS/east years in winter, but the difference is not so large compared with that in the west





Fig. 4. Same as Fig. 3, except showing correlation calculated from QBO west (1<sup>st</sup> row), QBO east (2<sup>nd</sup> row), ENSO warm (3<sup>rd</sup> row), ENSO cold phases (4<sup>th</sup> row), respectively.

phase. The signal shows poleward propagation in the troposphere from winter to early summer, but the stratosphere-troposphere signal is prominent in summer in HS/east years. Compared with HS/east years, propagation of the singal in the troposphere is rather fast, but persistence of the signal is short in LS/east years. Downward propagation of the QBO signal in the tropical stratosphere is also prominent in LS/east years.

Figure 6 shows the solar cycle modulation of the NAO with the effect of the ENSO cycle. In the case of the warm phase of the ENSO cycle (upper panels), extension of the winter NAO signal is again much larger in winter in HS/ warm than LS/warm years. The overall feature of the time evolution of the signal is very similar to the warm phase (Fig. 4) in HS years. It is interesting to note that the signal in HS/ warm years is relatively weaker from spring to early summer, but a relatively stronger signal reappears in summer. In fact, meridional tripole structure in the troposphere in JJ and stratospheric signal in AS is apparent. Comparing with the HS/warm years, the signal is stronger from spring to early summer in the troposphere in LS/warm years, although a small stratospheric signal still exist in summer.

In the case of the cold phase of the ENSO cycle (lower panels of Fig. 6), more vertical extension in winter is apparent in HS/cold years compared with LS/cold years. However, the core of the signal shifts more equatorward compared with the warm phase. It should be noted that the overall feature of the signal is very similar to the HS years (Ogi et al. 2003), and especially summer signal is very strong and shows strong AO-like signal from surface to upper stratosphere. In contrast, the signal in LS/cold years is a local tropospheric pattern in winter and the signal disappears very quickly, similar to the LS years.

### Journal of the Meteorological Society of Japan



Fig. 5. Same as Fig. 3, except showing correlation in HS or LS years under each phase of the QBO. Each panels shows, the correlation calculated from HS and QBO west (1<sup>st</sup> row), LS and QBO west (2<sup>nd</sup> row), HS and QBO east (3<sup>rd</sup> row), LS and QBO east phases (4<sup>th</sup> row), respectively. The contour interval is 0.1 and contours are drawn for absolute values greater than or equal to 0.6 and for zero. Shading is applied to regions where the absolute value of the correlation is greater than 0.5. Dashed lines indicate negative values.

## 4. Discussion and remarks

Present analysis shows that the solar cycle modulation of the winter-mean NAO is largely modified by other external factors of the QBO and ENSO cycle. Solar cycle modulation of the NAO in winter is more enhanced in the west phase of the QBO than the east phase. In this case, reappearance of the AO-like structure in summer is also more prominent in the west phase. In contrast, the signal is very suppressed in LS years in the westerly phase. This means that in the west phase of the QBO, effect of solar signal is much more amplified. Similar amplification of the solar signal is also found in the cold phase of ENSO cycle.

In the present analysis, we divided all the data into two subgroups according to three different external forcings of the solar cycle, QBO, and ENSO. This means that any sub-data from one forcing will contain about half common members from the other sub-data. So it should be noted that any two sub-data, such as HS and QBO-west, cannot be statistically independent, and about half data will be common, in general. In the present analysis, data for QBO-west and ENSO-cold has relatively higher common members ( $\sim 64\%$ ). Similarly, data for LS and ENSOcold has higher common members ( $\sim 61\%$ ). For the compound analysis, it should be noted that HS/cold and HS/west has 6 common years. This is only 55% for HS/west years but it is 67% for



Fig. 6. Same as Fig. 4, except showing correlation in HS or LS years under each phase of the ENSO cycle. Each panels shows the correlation calculated from HS and ENSO warm (1<sup>st</sup> row), LS and ENSO warm (2<sup>nd</sup> row), HS and ENSO cold (3<sup>rd</sup> row), LS and ENSO cold (4<sup>th</sup> row), respectively.

HS/cold years due to relatively small samples. So it is statistically difficult to separate the effect of HS/cold from that from HS/west in the present analysis.

Strength of zonal wind is largely modified according to the phase of the QBO. In fact, Holton and Tan (1980) found that in the east phase upward propagation of planetary waves take place in a more poleward region because zero zonal-wind line (called the critical latitude) is shifted poleward due to the existence of the easterly wind at the equator, and planetary wave can propagate only in the westerly wind area. As a result, zonal wind at the polar troposphere to the stratosphere becomes stronger (weaker) in the west (east) phase due to the activity of waves. Such a situation will appear on the QBO modulation of the NAO. It should be noted that the correlation analysis simply shows variation with the NAO indices and total patterns of each phase are not highlighted. To show variations in more detail, different types of analysis, such as composite analysis, will be needed.

Because the winter NAO signal extends to higher altitude in the easterly phase of the QBO and warm phase of the ENSO cycle than the other phases (Fig. 1), vertical extension in HS phase is expected to be enhanced in QBOeast and ENSO-warm phases. However, this was not seen. This means that the compound effect is due to some nonlinear interaction between respective factors.

To see the source of solar cycle modulation due to QBO, we performed analysis of EP flux, meridional circulation, temperature, and ozone



Fig. 7. Same as Fig. 4, except showing correlation of the EP flux (arrow) and the EP flux divergence (contoured or shaded) (1<sup>st</sup> row), the temperature (contoured or shaded) and the residual velocity (arrow) (2<sup>nd</sup> row), and ozone volume density (contoured or shaded) and the residual velocity (arrow) (3<sup>rd</sup> row) in the QBO west and HS years. Only arrows whose absolute value of correlations is greater than 0.6 are plotted.

as we did in the analysis of Kuroda et al. (2007). The assimilated ozone data we used here is the same as in Sekiyama et al. (2006). It is found that the overall features, including wave propagation, variability of the meridional circulation, and formation of ozone and temperature anomalies from spring to summer in HS/ west years are very similar to that those observed in HS years, although their variability is stronger (Fig. 7). In fact, in DJ wave propagation to the stratosphere becomes weaker and it produces anomalous positive EP flux divergence in the stratosphere, which then produces weaker Brewer-Dobson circulation and negative ozone anomaly. Such ozone anomaly is persistent until the next summer and creates anomalous negative temperature in the lower stratosphere, which in turn creates anomalous positive temperature by a downward flow to the troposphere mainly in JJ (Fig. 7). On the other hand, in the case of LS/west years, correlation of wave and ozone variability associated with the NAO is found to be very small (not shown). This analysis supports the hypothesis that activities of these quantities are linked together to create solar cycle modulation as is shown in Kuroda et al. (2007). Similar results are obtained for the solar cycle modulation under ENSO-cold phase. However, as these years are largely overlapped with QBO-west years, we do not show the result here.

In Fig. 7, we considered ozone as a memory of the winter-NAO to the following summer following the analysis of Kuroda et al. (2007). In contrast, Ogi et al. (2003) considered surface condition such as SST as a memory. To investigate the role of ozone and surface condition on the memory of the winter-NAO, controlled numerical experiment is needed in a future study.

As the ENSO-cold years coincide largely with the QBO-west year, most of the solar cycle modulation under ENSO-cold condition will be explained if that from QBO is explained. So we will consider only the possible mechanism of the solar cycle modulation by QBO effect here, although independent effect from ENSO may exist elsewhere.

Y. KURODA

Solar heating at the upper stratosphere creates anomalous zonal wind in the winter hemisphere through thermal-wind relationship. So zonal wind at the upper stratosphere becomes a strong westerly that extends to the polar troposphere through wave-mean flow interaction in early winter of HS yeas (Kuroda and Kodera 2002; Kodera and Kuroda 2002). On the other hand, QBO controls the equatorial wind and critical latitude for the upward and equatorward propagation of the planetary wave. In the westerly phase of the QBO, critical latitude is absent and planetary waves can propagate upward in lower latitude and the zonal wind at high latitude becomes stronger (Holton and Tan 1980). So in HS/west years, basic wind should be a stronger westerly that extends from the polar troposphere to the upper stratosphere in early winter. If the NAO act as one more wave source, associate planetary waves will effectively propagate the area of stronger westerly wind that extends to the upper stratosphere. As a result, variability associated with the NAO will extend from surface to upper stratosphere. In the easterly phase of the QBO, on the other hand, basic zonal wind in the polar troposphere will be weaker. Though solar activity should also control the zonal wind in the stratosphere, formation of the waveguide to the upper stratosphere will be insufficient to create larger variability associated with the NAO, even in HS years. More study will be needed to confirm the mechanism.

We used data separation of solar cycle and other factors based on average value. Though this is a simplest method for the separation, we should examine whether the result is very sensitive for the selection of each group to know the stability of the result. So we also tried to narrow each group by setting some threshold value. Calculation shows that the result is not very sensitive to small change of the threshold value. This indicates that the results obtained here have statistical validities.

Though we used observed 43-year data, this span of data is not long enough to examine the statistical argument for the compound effect on the solar cycle modulation of the NAO. Also, we could not deal with the solar-cycle, QBO, and ENSO independently by the observational data. To overcome these difficulties, a control experiment using a chemistry climate model (CCM) will be a most promising method. Tourpali et al. (2005) examined the solar cycle modulation of the AO by their CCM. Experiment using our CCM will be a future study.

In this study, we had examined solar cycle effect on the winter-NAO. However, for the modulation of the NAO, there may be other factors, including compound effect of the QBO and ENSO or volcanic effect and so on. For the volcanic effect on solar cycle modulation of the NAO, we examined the effect by removing the years with volcanic eruption. The result shows that the effect is small. The other compound effect should also be examined in a future study.

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898

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