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Combined solar and QBO effects on the modes of low-frequency atmospheric variability in the Northern Hemisphere

Radan Huth [a,*], Lucie Pokorná [a], Josef Bochníček [b], Pavel Hejda [b]

[a] Institute of Atmospheric Physics, Prague, Czech Republic
[b] Institute of Geophysics, Prague, Czech Republic

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ABSTRACT

We examine joint effects of the solar activity and phase of the quasi-biennial oscillation (QBO) on modes of low-frequency variability of tropospheric circulation in the Northern Hemisphere in winter. The winter months (December–March) are stratified by the solar activity into two (below/above median) classes, and each of these classes is subdivided by the QBO phase (west or east). The variability modes are determined by rotated principal component analysis of 500 hPa heights separately in each class of solar activity and QBO phase. Detected are all the modes known to exist in the Northern Hemisphere. The solar activity and QBO jointly affect the shapes, spatial extent, and intensity of the modes; the QBO effects are, however, generally weaker than those of solar activity. For both solar maxima and minima, there is a tendency to the east/west phase of QBO to be accompanied by a lower/higher activity of zonally oriented modes and increased meridionality/zonality of circulation. This means that typical characteristics of circulation under solar minima, including a more meridional appearance of the modes and less activity of zonal modes, are strengthened during QBO-E; on the other hand, circulation characteristics typical of solar maxima, such as enhanced zonality of the modes and more active zonal modes, are more pronounced during QBO-W. Furthermore, the zonal modes in the Euro-Atlantic and Asian sectors (North Atlantic Oscillation, East Atlantic pattern, and North Asian pattern) shift southwards in QBO-E, the shift being stronger in solar maxima.

1. Introduction

About 20 years ago, Labitzke (1987) discovered that the relationship between the solar activity and the North Pole 30 hPa temperature (or height) in winter emerges only if data are stratified by the phase of the quasi-biennial oscillation (QBO): Under the west phase of QBO (QBO-W), the correlation between the solar activity and polar stratospheric temperature (height) is strongly positive, whereas under QBO's east phase (QBO-E), the correlation is weakly negative (e.g., van Loon and Labitzke (1994)). This result was based on mere 30 years of data; nevertheless, after updating by 20 recent years, the relationship still holds (Labitzke, 2005), and does so even after adding reconstructed data back to 1942 (Labitzke et al., 2006). The solar effect at the North Pole is a part of the hemisphere-wide response of the stratosphere. In QBO-W, it consists of an intensification of the Brewer–Dobson circulation and downwelling and warming over the Arctic under solar maxima (and vice versa under solar minima); in QBO-E, the solar maxima are connected with the weakening of the Brewer–Dobson circulation and enhanced downwelling and warming over the tropics and subtropics (e.g., Labitzke et al., 2006). Since the signal propagates from the stratosphere down to the troposphere, joint effects of the solar activity and the QBO phase were also uncovered in the troposphere and near surface, e.g., in temperature, sea level pressure, geopotential height, and wind fields (van Loon and Labitzke, 1988; Barnston and Livezey, 1989; Venne and Dartt, 1990; Bochníček et al., 2001), latitudinal position of storm tracks (Tinsley, 1988), blockings (Barriopedro et al., 2008) and correlations of the Northern Hemisphere relative angular momentum with geopotential heights (de la Torre et al., 2006).

Recently, Boberg and Lundstedt (2002), Ruzmaikin and Feynman (2002), Kodera (2003), Ogi et al. (2003), Bochníček and Hejda (2005), Kuroda and Kodera (2005), and Huth et al. (2006, 2007) identified effects of solar activity on various modes of low-frequency tropospheric circulation variability, including the North Atlantic Oscillation and the Northern and Southern Annular Modes. These effects were uncovered without any stratification by the QBO phase. Only Haigh and Roscoe (2006) found that the Northern and Southern Annular Modes in the troposphere depend much more strongly on the product of solar activity with the QBO than on each of them if considered individually.

The question therefore arises of whether a stratification by the QBO phase would modulate the solar effects on the circulation variability modes, providing a motivation for the present study. We analyse the modes of low-frequency variability in 500 hPa

* Corresponding author. Tel.: +420 2 72 76 43 36, +420 2 72 01 60 46; fax: +420 2 72 76 37 45.
E-mail address: huth@ufa.cas.cz (R. Huth).

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heights by means of the methodology similar to that used in Huth et al. (2006) (hereafter referred to as H06): the data are stratified by both the level of solar activity and QBO phase, the modes are identified by means of principal component analysis (PCA) in each of the solar/QBO classes separately, and the spatial structure of the modes is compared between different classes and the differences are tested for statistical significance.

2. Data, methods, and display of results

The analysis is based on monthly mean values for the extended winter season (December–March). The period covered starts in January 1953 and ends in March 2003. The solar activity is characterized by the solar radio flux at 10.7 cm (F10.7). The QBO is defined by the mean equatorial zonal wind between 50 and 40 hPa (Naujokat, 1986; Labitzke et al., 2002, updated); the QBO data were obtained from the Free University of Berlin by the courtesy of Dr. B.Naujokat. The dataset is stratified into four groups by dividing it into two halves by the median value of F10.7 and by the QBO phase (east/west). The number of months in each group are displayed in Table 1. We repeated the whole analysis for two other stratifications, both into six groups: (i) solar activity divided by the terciles and QBO by the phase (3×2 groups), (ii) solar activity divided by the median and QBO by the terciles (2×3 groups). The results based on these additional stratifications are similar to those reported below, but because of smaller sample size tend to be less stable; therefore we limit ourselves to displaying results for the 2×2 stratification only. We also present for reference results of the analyses conducted for data (i) stratified by the solar activity only, (ii) stratified by the QBO phase only, and (iii) not stratified, i.e., for the whole dataset.

Modes of tropospheric circulation variability are identified in the 500 hPa geopotential heights. The source of data is NCEP/NCAR reanalysis (Kalnay et al., 1996). The analysed area is the Northern Hemisphere north of 20°N (inclusive). We use the data in the $5^\circ\times5^\circ$ horizontal resolution, which is fully sufficient thanks to large spatial autocorrelations in the 500 hPa height fields. The reduction of resolution relative to the original $2.5^\circ\times2.5^\circ$ one was achieved by simply taking every second latitude and longitude. Anomalies from monthly pointwise climatology, weighted by the square root of cosine of the latitude, form the data matrix. PCA is applied in an S-mode (columns of the data matrix correspond to gridpoints, rows to months), with covariance as a similarity matrix. Modes of variability are defined by orthogonally rotated PCA, with a VARIMAX criterion used for rotation (more details on the rotation of principal components and its various criteria can be found in Richman, 1986). The number of principal components (PCs) to retain for rotation is determined in accordance with the criterion by O'Lenic and Livezey (1988). In all the analyses discussed here, the appropriate number of PCs is 9. We stick to the nomenclature of the modes introduced by Barnston and Livezey (1987) (hereafter referred to as BL).

The approach taken here, i.e., conducting separate PCAs in each solar activity/QBO phase group, allows finding modes intrinsic to each group. It in fact supposes there may be different sets of modes in each group. There is another potential approach, consisting in finding one set of modes in the full dataset and projecting the modes into the individual groups. Here, the existence of an identical set of modes in all groups is supposed, which makes it difficult or even impossible to detect, for example, a merger of two modes or disappearance of a mode in a specific group. For these reasons, we prefer the former approach.

Table 1
Number of months in the groups of solar activity/QBO phase.

	Solar		
	Low	High	All
QBO			
East	42	42	84
West	60	59	119
All	102	101	203

The modes are displayed as maps of normalized loadings, i.e., of correlations of PCs with the 500 hPa heights. Results for each mode are displayed in one figure, the modes being ordered, and in Section 5 discussed, geographically from the North Atlantic/Europe through Asia to the North Pacific/North America, in the following sequence: North Atlantic Oscillation (NAO; Fig. 1); East Atlantic pattern (EA; Fig. 2); Eurasian pattern, type 1 (EU1; Fig. 3); Eurasian pattern, type 2 (EU2; Fig. 4); North Asian pattern (NAs; Fig. 5); Pacific/North American pattern (PNA; Fig. 6); West Pacific Oscillation (WPO; Fig. 7); Tropical/Northern Hemisphere pattern (TNH; Fig. 8); and East Pacific pattern (EP; Fig. 9). The additional modes, not corresponding to any of those described by BL, are summarized in Fig. 10. Each figure consists of nine map panels. The rows correspond to the QBO phases, whereas the columns correspond to different levels of solar activity. Top (bottom) row displays PC loadings for QBO-E (QBO-W), while the middle row displays loadings regardless of the stratification by QBO. Left (right) column shows PC loadings for low (high) solar activity, the middle column showing loadings regardless of the solar activity stratification. The degree of importance of the modes, i.e., the variance explained and their order, together with the cumulative variance explained by the nine leading modes, are shown in Table 2.

The differences of the normalized loadings between the high and low solar activity and between the W and E QBO phase are tested for their statistical significance analogously to H06. Briefly speaking, the conventional test for the equality of correlation coefficients is employed. First, the correlation coefficients are Fisher-transformed, and then the test statistic is calculated, which is normally distributed under the assumption that the hypothesis on the equality of correlations is true. We do not take into account temporal autocorrelation in the series. H06 demonstrated that this neglection results in the test being slightly liberal, i.e., the hypothesis of the equality of the correlations is rejected at more gridpoints than it should have been rejected; however, this effect is fairly small even in the extreme combination of a small sample size and the highest possible autocorrelation of both time series. The areas where the normalized loadings are not equal at the 5% significance level are displayed by shading and thick grey lines in Figs. 1–9. The areas with significant differences between high and low solar activity are denoted by thick grey lines in the middle column panels of Figs. 1–9. So, the significant differences between high and low solar activity under QBO-E are marked in the upper middle panels (b), the same under QBO-W is shown in lower middle panels (h), while significant differences between high and low solar activity without stratification by QBO are in central panels (e). Analogously, the areas with significant differences between QBO phases are marked by grey shading in Figs. 1–9: the significant differences between QBO-E and QBO-W under low/high solar activity are in the left/right central panels (d)/(f), while the differences between the QBO phases without stratification by solar activity are in the central panel (e).

3. Effects of solar activity

First of all, results of the effects of solar activity alone are briefly reviewed. They are described in more detail, and for