Stratospheric Bimodality: Can the Equatorial QBO Explain the Regime Behavior of the NH Winter Vortex?

BO CHRISTIANSEN
Danish Meteorological Institute, Copenhagen, Denmark

(Manuscript received 30 October 2009, in final form 16 February 2010)

ABSTRACT

The Northern Hemisphere extended winter mean stratospheric vortex alternates between a strong and a weak state, which is manifested in a statistically significant bimodal distribution. In the end of the 1970s a regime change took place, increasing the frequency of the strong phase relative to the weak phase. This paper investigates the connection between the regime behavior of the vortex and the equatorial quasi-biennial oscillation (QBO) in three different datasets. Although there are some differences between the datasets, they agree regarding the general picture. It is found that stratospheric equatorial wind between 70 and 8 hPa shows a bimodal structure in the Northern Hemisphere winter. Such bimodality is nontrivial as it requires only weak variability in the amplitude. Unimodality is found above 8 hPa, where the semiannual oscillation dominates. A strong coincidence is found between strong (weak) vortex winters and winter in the westerly (easterly) QBO regime. Furthermore, the change of the vortex in the late 1970s can be related to a change in the QBO from a period with strong bimodality to a period with weak bimodality. Careful consideration of the statistical significance shows that this change in the QBO can be a random process simply related to the annual sampling of the QBO. Finally, previous findings of phase locking between the QBO and the annual cycle are considered; it is shown that the phase locking is related to the seasonal variations in the bimodality of the QBO.

1. Introduction

The existence of multiple regimes in the low-frequency atmospheric circulation is a question that has attracted much interest over the last decades (e.g., Sutera 1986; Mo and Ghil 1988; Michelangeli et al. 1995; Corti et al. 1999; Smyth et al. 1999; Christiansen 2005; Hannachi 2007; Ambaum 2008, and references therein) because of its potential for long-range weather forecasting and its importance for climate change. The latter was pointed out by Palmer (1993) and has gained even more significance by the recent interest in “tipping points” — large irreversible changes in the climate system triggered by small forcings (Lenton et al. 2008). The identification of multiple regimes has proven to be challenging both because of the relative short period with observations (Hsu and Zwiers 2001; Christiansen 2002; Stephenson et al. 2004) and because of methodological difficulties (Sura et al. 2005; Christiansen 2007).

Christiansen (2003) showed that the stratospheric Northern Hemisphere (NH) winter mean vortex jumps between two well-separated regimes: a strong vortex regime with strong stratospheric winds and low polar temperatures and a weak vortex regime with weak stratospheric winds and high polar temperatures. Furthermore, a regime shift toward the strong vortex regime at the end of the 1970s was detected. This shift is manifested by a substantial change in the frequencies of the two regimes. The stratospheric regimes and the regime shift were found to have tropospheric impacts (see also Hannachi 2007). A recent work (Christiansen 2009) applying projection pursuit to the extratropical winter circulation in both the troposphere and the stratosphere confirmed the significant bimodality in the stratosphere while the circulation in the troposphere only shows weaker deviations from Gaussianity such as skewness and platykurticity (flatness). Christiansen (2009) only found significant bimodality in the stratosphere for winter means in contrast to Coughlin and Gray (2009), who found bimodality in daily values using a cluster technique.
The stratospheric regime change at the end of the 1970s coincides with a shift of the Southern Oscillation index (Trenberth 1990) and with an eastward shift in the pattern of the North Atlantic Oscillation (Lu and Greatbatch 2002). It has also been found that the North Atlantic Oscillation correlates with solar variations in the 1980s and 1990s; the correlation is weak or absent in earlier decades (Thejll et al. 2003). Furthermore, the stratospheric regime shift is almost concurrent with a strong almost steplike decrease in stratospheric ozone (Fioletov et al. 2002). We also note that Swanson and Tsonis (2009), in addition to a shift in the late 1970s, suggest a recent shift around the year 2000 in the global mean surface temperature.

Holton and Tan (1980) documented that the extratropical NH winter vortex is connected to the equatorial quasi-biennial oscillation (QBO) so that on average the vortex is strongest when the QBO is westerly (measured at 50 hPa). Since they included only 16 winters, the statistical significance of this result is necessarily weak; succeeding studies have shown that strong low-frequency variations exist in the connection between the vortex and the QBO [Labitzke 1987; see also the reviews by Baldwin et al. (2001) and Gray (2010)]. Recently, Lu et al. (2008) confirmed the Holton–Tan relationship in data covering 1968–2006. They also reexamined the decadal variations and found that the Holton–Tan relationship was significantly weakened in the 1977–97 period.

The QBO phase transitions are not homogeneously distributed over the year but have been shown to cluster at certain seasons (Dunkerton 1990; Baldwin et al. 2001; Pascoe et al. 2005). Anstey and Shepherd (2008) found that the seasonal alignment of the QBO phase transitions influences the NH vortex, and they, in particular, suggested that the weak Holton–Tan relationship in 1977–97 is related to variations in the phase alignment of the QBO.

Encouraged by this recent progress, we will here investigate in detail the connection of the QBO to the regime behavior of the vortex—with regard to both the winter to winter variability and the regime shift. The guiding principle of the present paper is that the oscillatory nature of QBO through the Holton–Tan relationship makes it a possible source of bimodality of the vortex, and that the length of its period between 20 and 36 months could result in low-frequency variability when sampled annually (Gray and Dunkerton 1990). It is therefore possible that the regime shift could be chance occurrence with no need for any additional physical explanation. In our analysis we will strongly emphasize tests of the statistical significance to compensate for the limited sample size.

The rest of the paper is organized as follows. In section 2 we describe the data and the methodology. In section 3 we review the bimodality of the vortex and in section 4 we deal with the statistical connection between these bimodalities; section 5 investigates whether the regime shift at the end of the 1970s could be a chance occurrence. In section 7 we reinvestigate the seasonal alignment of the QBO phase transitions, and the paper closes with the conclusions in section 8.

2. Data and methods

We use three different datasets to define the QBO and the NH vortex. Daily mean zonal winds and geopotential heights have been obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005). The NCEP–NCAR reanalysis has a top level at 10 hPa and covers the years 1948–2008, whereas ERA-40 reaches higher, to 0.1 hPa, but covers a brief period, 1959–2001. We have also used the monthly mean QBO index from the Free University of Berlin (FUB) (Naujokat 1986). This index is composed of observations from three equatorial radiosonde stations. The data exist on six levels from 70 to 10 hPa and we use the period 1955–2008. The Free University of Berlin also provides monthly means of geopotential heights in the NH at 30 hPa during the period 1957–97 (Pawson et al. 1993). The FUB data are based on radiosondes and therefore independent of any inhomogeneities in satellite coverage. Thus, the three datasets complement each other in vertical and temporal coverage as well as in the underlying data material.

As in Christiansen (2003), we are interested in the NH extended mean winters, October–March (note that the winters are identified by the year that includes January). A measure of the vortex has been obtained as the leading principal component (PC) of the mean winter geopotential height at 20 hPa (30 hPa for the FUB data) calculated from data north of 20°N after each data point has been weighted with the square root of the area it represents. Christiansen (2003) identified the regime behavior of the stratospheric vortex in NCEP–NCAR data from the period 1948–2001. The results were confirmed by using 1957–97 data from FUB. We will mainly be interested in the QBO at 50 hPa where previous studies have shown that the connection to the extratropics is strongest (e.g., Baldwin and Dunkerton 1998). In the reanalyses the QBO is represented by the equatorial zonal-mean zonal wind.

Also as in Christiansen (2003), probability density estimates are calculated by the kernel procedure with
The statistical tests will mainly be based on the Monte Carlo approach. A statistic will be defined that measures the attribute under interest. More precisely, the statistic should measure the deviation from the null hypothesis. For example, for a null hypothesis of unimodality a statistic will be defined that measures the strength of bimodality or multimodality. Likewise, for a null hypothesis of serially independent data the statistic will measure the serial correlations. The value of the statistic $s_{\text{orig}}$ is calculated for the original data and this value is compared to similar values $s_i$, $i = 1 \ldots m$, calculated for an ensemble of surrogate data with $m$ members. If few of the $s_i$ values are larger than $s_{\text{orig}}$ we will reject the null hypothesis. More quantitatively, a $p$ value is calculated as the fraction of surrogates with $s_i > s_{\text{orig}}$. The surrogates should fulfill the null hypothesis but in all other aspects be statistically similar to the original data. This is a point of utmost importance as the null hypothesis is basically defined by the difference between the surrogates and the original data. For example, consider a situation where we want to test for non-Gaussianity in a dataset. Consider further that surrogates are drawn serially independently from the best Gaussian fit and a small $p$ value is found (using, say, skewness as the statistic). In this situation we can only reject Gaussianity if we know that the original data are not serially correlated.

In the following we will often be interested in the null hypothesis of unimodality. As a measure of the deviation from unimodality we will mainly use the critical smoothing (Silverman 1986). The critical smoothing measure is defined as the smallest smoothing parameter $h_{\text{crit}}$ that gives a unimodal distribution. We will additionally use the depth measure (Christiansen 2003) and the measure defined by Nason and Sibson (1992). See Christiansen (2009, particularly his Table 1) for more details of these statistics.

In the following sections we will relegate the details of the surrogates to footnotes in order not to disrupt the flow of the paper.

### 3. Bimodality of the vortex

In this section we briefly elaborate on the results of Christiansen (2003) regarding the bimodality of the winter vortex. We now have seven more years in the NCEP–NCAR dataset and we will also compare with the ERA-40 data.

The leading empirical orthogonal function (EOF) has for all datasets the same strong annular structure with a node at 45°N (see Fig. 2 in Christiansen 2003). The explained variances of the leading PC are 52%, 51%, and 50% for the FUB, NCEP/NCAR, and ERA40 data in their full periods. For each dataset the leading PC is very well separated from the second PC, which explains around 13%–16% of the variance. For the common period—1959–97—the explained variances of the leading mode are all 50%.

The top panel of Fig. 1 shows time series of the leading PCs for the extended winters for all three datasets. The three datasets agree well concerning the long-term variability of the vortex, although minor differences are found for individual years. We find that these differences are mainly due to differences in the data and are only to a smaller degree related to the different periods of the EOF analysis.

Figure 2 shows the corresponding probability densities and histograms both for the full periods and the common period. Also, probability densities are shown separately for the periods before 1980 and after 1979. The bimodality is clear in both the NCEP–NCAR and the FUB data for both the full period and the common period. The bimodality is less clear in the kernel density for the ERA-40 data but bimodality is apparent in the histogram. Of the additional seven winters in the NCEP–NCAR data compared to Christiansen (2003), four fall in the strong vortex regime and three in the weak vortex regime. As in Christiansen (2003) the bimodality is significant to the 10% level in the NCEP–NCAR data, but not in the two other datasets. This result is confirmed when measures of bimodality other than that of Christiansen (2003) are used.

---

1 The cross-validation function shows a rather broad minimum and the optimal value of $h$ is therefore not well defined. In general the optimal value $h_{\text{opt}}$ depends on the number of samples $n$, the width of the distribution, and to a lesser degree on the form of the distribution. Here, we have used the approximation

$$h_{\text{opt}} = cA^{4/5},$$

with $A = \min[\rho, R/1.34]$, where $\rho$ is the standard deviation and $R$ is the interquartile range (Silverman 1986, p. 47). The constant $c$ is set to 0.75. In the cases considered in the present paper, this procedure gives values near the middle of the broad minimum of the cross-validation function.
The shift in 1979 is very clear in all three datasets: winters before 1979 mainly fall in the weak regime while winters after 1979 mainly fall in the strong regime. However, in both subperiods both regimes are visited often enough to give rise to bimodality in the densities. Christiansen (2003) found that this shift was statistically significant in the NCEP–NCAR dataset. However, Christiansen (2003) did not consider the effect of the autocorrelation at lag 2 (Table 2). For the first two lags the corresponding distribution of the original data is called the equatorial zonal-mean zonal wind. The FUB QBO is found as the equatorial zonal-mean zonal wind. The FUB QBO is composed from observations of three equatorial stations.

The three datasets show the same sign for nearly all winters except for winters with weak winds and a few early years (e.g., 1952 and 1953).

The probability densities for the three different QBO datasets are shown in Fig. 3. The bimodality is confirmed in all three datasets when all available data are considered. In the ERA-40 and the FUB data the westerly (positive winds at 50 hPa) phase is dominant while the two peaks are comparable in the NCEP–NCAR data. For all datasets the QBO is bimodal in the period before 1980; for the period after 1979 only NCEP–NCAR does not show a clear bimodality. However, a considerable difference is seen when the distributions in the two periods are compared. Both ERA-40 and NCEP–NCAR show a shift toward westerly phases in the later period while the distributions for FUB are almost identical for the two periods. This discrepancy between the datasets is partly a consequence of the different periods they cover. Figure 3 also shows the distributions for the common period, 1959–2001, and here the difference between the two subperiods is comparable in the three datasets.

For the whole period the bimodality of the NCEP–NCAR data is significant to the 5% level using the surrogate method of Christiansen (2003) if the critical smoothing is used as the measure of bimodality (Table 1). The weakest significance is found for the ERA-40 data. For the other measures of bimodality similar or even stronger significance is obtained.

There is an important consideration to be made here. The test of unimodality used above requires the data to be serially independent. This is not the case for the winter means of the QBO. In fact, because of the oscillatory nature of the QBO there is a very strong negative autocorrelation at lag 1 and a weaker positive autocorrelation at lag 2 (Table 2). For the first two lags the correlations are very significantly different from zero for all three datasets. Fortunately, the bimodality of the

FIG. 1. (top) The October–March extended winter mean vortex at 20 hPa (30 hPa for FUB) and (bottom) the QBO at 50 hPa for the three datasets. The vortex is defined as the leading PC of the extended winter mean geopotential height north of 20°N. From the reanalysis the QBO is found as the equatorial zonal-mean zonal wind. The FUB QBO is composed from observations of three equatorial stations.
FIG. 2. Probability densities of the October–March extended winter mean vortex at 20 hPa (30 hPa for FUB) for the three datasets—
(top) ERA-40, (middle) NCEP–NCAR, and (bottom) FUB—for (left) all available years and (right) only the common period (1959–97). Kernel estimates are shown for the total available period (thick full curves), the period before 1980 (broken curves), and the period after 1979 (thin full curves). The histogram estimate of the total available period is also shown, with the positions of the individual years indicated and years before 1980 shaded.
Fig. 3. Probability densities of the October–March extended winter QBO at 50 hPa for the three datasets. Details are as in Fig. 2.
The statistical significance of the bimodality of the QBO shown for the three different datasets and for three measures of bimodality. The p values are shown calculated both from independent surrogate data and surrogate data with the same autocorrelation structure as the original (in parentheses). See footnotes 2 and 4 for more detail.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Critical smoothing</th>
<th>Depth</th>
<th>Nason</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-40</td>
<td>0.18 (0.33)</td>
<td>0.02 (0.05)</td>
<td>0.03 (0.04)</td>
</tr>
<tr>
<td>NCEP–NCAR</td>
<td>0.05 (0.05)</td>
<td>0.06 (0.05)</td>
<td>0.09 (0.07)</td>
</tr>
<tr>
<td>FUB</td>
<td>0.07 (0.07)</td>
<td>0.03 (0.02)</td>
<td>0.02 (0.01)</td>
</tr>
</tbody>
</table>

distributions is significant also if the autocorrelations are included in the surrogates, as also reported in Table 1.

The bimodality observed in the winter means of the QBO is related to a nontrivial property of its low-frequency variability. Figure 4 shows the probability density of the equatorial zonal-mean zonal wind as function of altitude (from the ERA-40 reanalysis). This figure is based on monthly means and includes all 12 calendar months. The winds in each vertical level have been normalized to zero mean and unit variance. The bimodality is clearly seen for altitudes between 70 and 8 hPa where the QBO dominates. The bimodality is significant to the 5% level between 10 and 50 hPa and to the 10% level between 7 and 70 hPa, taking serial correlations into account. This is in strong contrast to the behavior above 8 hPa where the equatorial semiannual oscillation denominates and the distribution is unimodal. For bimodality to appear it requires that the oscillation has an approximately constant amplitude over the 44 yr, which is the case for the QBO but not for the semiannual oscillation.

5. Bimodality of the vortex: The influence of the QBO

We showed in section 4 that the winter means of the QBO are significantly bimodal and in section 3 that the bimodal nature of the vortex described in Christiansen (2003) also holds when the latest seven winters are included. We also described a shift in the QBO at the end of the 1970s concurrent with the shift in the vortex. In this section we investigate the possible connection between these two observed bimodalities and shifts. To this end we will use the NCEP–NCAR data, which cover the longest period.

Already the time series in Fig. 1 indicate that a connection may exist. This is substantiated in Fig. 5 where the probability densities of the vortex are stratified according to the phase of the QBO. When data from the whole NCEP–NCAR period 1949–2008 is used (Fig. 5, top) the bimodal structure of the vortex can be very well “explained” by the phases of the QBO. More specifically, if only easterly QBO winters are included, the probability density of the vortex is strongly concentrated over the weak regime (with the winters of 1990 and 1997 as the most prominent exceptions). On the other hand, if only westerly QBO winters are considered, the probability density peaks at the position of the strong vortex regime. Again, exceptions do occur, resulting in a soft shoulder near the position of the weak vortex regime (depending on h).

Given the nonstationarity of both the vortex and the QBO (manifested as the shift around 1979), it is important

---

4 We find the critical distribution \( P_c \) or the optimal distribution \( P_{opt} \) as before. Then the original time series is phase-randomized to give a new series \( y \) with the same autocorrelations as the original. The samples \( y \) are drawn from a Gaussian distribution \( P_G \) and now transformed to samples \( x \) from the critical or optimal distribution by \( \int_{-\infty}^{x} P_c(z) \, dz = \int_{-\infty}^{x} P_{opt}(z) \, dz \) or \( \int_{-\infty}^{x} P_{opt}(z) \, dz = \int_{-\infty}^{x} P_{opt}(z) \, dz \). This procedure is described in Christiansen (2005); a more precise procedure is given in Schreiber and Schmitz (1997).

---

FIG. 4. Probability density of the monthly equatorial zonal-mean zonal wind as function of altitude. For each vertical level the winds have been normalized to unit variance. Data are from the ERA-40 reanalysis. All 12 calendar months are included.
to investigate whether the connection shown above is only a consequence of a common shift or if it shows up in both subperiods. In the early subperiod (before 1980; Fig. 5, middle) the situation is clear and almost identical to the result for the whole period. Only 3 out of 20 winters with easterly QBO have a strong vortex and only 3 out of 11 winters with westerly QBO have a weak vortex. For the later period the situation is less clear (after 1979; Fig. 5, lower panel). Here, only 2 out of 14 winters with westerly QBO have a weak vortex while around half of the winters with easterly QBO have a strong vortex.

This difference between the subperiods is consistent with the clear bimodality found in the QBO in the early subperiod and the absence of bimodality in the later subperiod (Fig. 3).

Similar results are found for the two other datasets, thus confirming the robustness. We have not been able to identify a statistical test that considers the connection of bimodality in one time series with the bimodality of another and separates it from a simple linear correlation as found by Lu et al. (2008). However, in Fig. 6, which shows the two-dimensional probability density in the space spanned by the QBO and the vortex, the two regimes are very clearly separated by a diagonal trough. Two independent but bimodal time series would not show that kind of bimodality in the two-dimensional probability density and neither would linearly correlated but unimodal time series. Figure 6 suggests, but certainly does not prove, that the connection between the vortex and the QBO is related to their common bimodal structure. Again we note the exceptional behavior of the winters 1990 and 1997.

6. The low-frequency variability of the QBO: A chance occurrence?

Both the QBO and the vortex have undergone low-frequency variability manifested as a shift in the last half of the 1970s, as can readily be seen from Fig. 1 and as we elaborated on in the previous sections. Before physical forcings (e.g., volcanic eruptions, the El Niño–Southern Oscillation, the sun, or stratospheric ozone depletions) are invoked as explanations, we should consider the simpler alternative that the low-frequency variability is a chance occurrence.

The interesting features of the observed QBO are that it shows a bimodal structure if all years are considered and that it has approximately 20 consecutive years (1979–99) with little bimodality. The question we will pose is therefore how common it is to find 20 consecutive years without bimodality in relevant surrogate time series that shows a bimodality of the same strength as the QBO when all years are considered.
There is a potential pitfall that was not realized in Christiansen (2003) where a similar question was asked for the vortex. If we ask how unusual the seemingly abnormal behavior in 1979–99 is, we tacitly assume that this period is special while we probably would be equally puzzled if any other 20-yr period showed a similar deviation from the long-term distribution. Instead of asking about the probability of the period 1979–99 being abnormal, we should ask about the probability of any consecutive 20-yr period being abnormal. It is obvious that the latter broader view—a variant of field statistics—will decrease the probability of rejecting the null hypothesis that the QBO is drawn from the same probability density (Fig. 3, full curve in left panel) for the whole period.

The statistic used to measure the decadal variability in the probability distribution should reflect the considerations above. For the surrogates we therefore search all subperiods of 20 consecutive years and identify the one with the weakest bimodality. The statistic is then the measure of bimodality in this subperiod.

The relevant surrogate time series should be drawn from the optimal bimodal probability density (Fig. 3). As discussed in section 4, the QBO has serial correlations and these should be mimicked in the surrogates. However, as for the bimodality in section 4 we find that the effect is negligible. See footnotes 3 and 4 for details about the generation of the surrogates.

We therefore define the p values as the fraction of surrogates that have as strong a bimodality in the whole period as the original QBO and where the weakest bimodality in any consecutive 20-yr period is weaker than the bimodality in the 1979–99 period in the original QBO. When considering all consecutive 20-yr periods, these p values are 15%, 28%, and 47% for NCEP–NCAR, FUB, and ERA-40, respectively, and the null hypothesis can therefore not be rejected. Thus, the low-frequency variability in the winter QBO can easily be a chance occurrence with no need for any special physical explanation. We note that if the focus only is on the 1979–99 period (as erroneously in Christiansen 2003), p values of 12%, 4%, and 12% make it difficult to reject the null hypothesis. The results above were obtained using the critical smoothing as the measure of bimodality but similar results are found with the other measures.

7. Bimodality of the QBO and the annual cycle

In previous sections we have focused on the extended winter means where we have found a clear bimodality in the QBO. A similar bimodality was observed for monthly means when considering the whole calendar year (Fig. 4). Previous work has indicated that the timing of the QBO phase transitions is related to the annual cycle (Dunkerton 1990). In this section we will investigate how the bimodality and its seasonal variations are related to the partial phase locking of the QBO. We expect that bimodality might be concentrated in seasons with few phase transitions.

The probability density of the QBO is shown as function of month in Fig. 7. All months show bimodality except April, May, June, and July, while the strongest bimodality is observed in the extended winter months, particularly the last months of the year. To quantify this observation we calculate $h_{crit}$ for each month (blue curve in Fig. 8), which confirms the strong bimodality in the last months of the year. Considering monthly means, Gray et al. (2004) found that the only significant Holtan–Tan relationship was found in November. This is the month in which we find the strongest bimodality and in which the bimodality is strong in both subperiods (Fig. 7, middle and lower panels).

To test the significance of the annual variability in the bimodality, we compare the monthly $h_{crit}$ with similar curves obtained from surrogate data. It is now important that surrogates have the same quasi-periodic structure as the original QBO but that the length of one period is independent of the length of the previous period. To accomplish this we construct daily resolved surrogates by resampling segments of the original QBO.
are defined as the period between two minima. A re-
realization of the surrogate data is shown in Fig. 9 together
with the original QBO. In this figure some corresponding
periods are indicated.

In Fig. 8 \( h_{\text{crit}} \) is shown for 100 randomly generated sur-
rogates. We see that the excess bimodality from August
to December is significant—it would happen only rarely
if the length of one QBO period was independent of
the length of the previous period. From a batch of
1000 surrogates we find that the probability of having
any five consecutive months with higher values of \( h_{\text{crit}} \)
than that found in August–December for the original
QBO is 0.02.

This result relates to previous findings (Dunkerton
1990) that the phase of the QBO shows some locking
to the annual cycle. However, while the literature agrees
that easterly/westerly transitions occur mostly in the
spring–summer season, there is some confusion about
westerly/easterly transitions. Dunkerton (1990) and
Hampson and Haynes (2006) find these transitions to
cluster in the autumn–winter season while Baldwin et al.
(2001), extending the work by Pawson et al. (1993), and
Pascoe et al. (2005) find clustering in the spring–summer
season. Less well-defined clustering is found by Anstey
and Shepherd (2008). Possible explanations for this con-
fusion may be the different datasets involved, the differ-
et altitude used to define the QBO, and differences in
the algorithms used to identify the transitions. Here we
present the transitions from the three datasets found with
the same algorithm and for a QBO at 50 hPa.

To identify the transitions we first remove the annual
cycle from the daily resolved QBO. Then we apply a
low-pass filter to remove variability faster than half a
year. From this filtered time series the months of the
westerly/easterly and easterly/westerly transitions are
determined. The phase transitions can differ by a few
months between the different datasets, but in all datasets

5 First, the \( N \) periods of the original QBO are found (\( N = 25, 18, \) and 23 for NCEP–NCAR, ERA-40, and FUB, respectively) as the
period between two consecutive minima in the daily QBO series
where subannual variability has been removed by a low-pass
Fourier filter. A daily resolved surrogate time series is now com-
posed by concatenation of \( N \) randomly chosen segments. Each
segment has the time development of a randomly chosen period of
the original QBO and the length randomly chosen from the dis-
tribution of original periods. From the daily resolved surrogate
time series the extended winter means are then calculated. The
daily resolved surrogates are therefore sampled from the same
probability distribution as the original daily QBO. Autocorrela-
tions are the same for the surrogates and the original QBO out
to the typical period of the QBO. For winter means or monthly means
the correlations and distributions of the surrogates are the same as
for the original QBO if there is no relation in the original QBO
between one period and the next.

Fig. 7. Probability density of the monthly equatorial zonal-mean
zonal wind at 50 hPa as function of season for (top) 1948–2008,
(middle) 1948–79, and (bottom) 1980–2008. Data are from the
NCEP–NCAR reanalysis.

(Fig. 10) the transitions cluster around May–June, with
more transitions in the first half of the year than in the
last. The same seasonality is found for westerly/easterly
and easterly/westerly transitions, confirming the result of
Baldwin et al. (2001). The statistical significance is shown in Table 3. The significance is calculated by considering the number of transitions in intervals of one, three, or five consecutive months. For each of these three cases the number of transitions is calculated for all 12 possible intervals (centered on each of the calendar months) and the statistic is the chosen as the largest of these 12 numbers. The statistics from the original QBO are compared to similar statistics obtained by drawing (the same total number of) transitions randomly with equal probability for each month. Alternatively, we compare with results obtained by drawing the interval between two transitions randomly from the observed distribution (as in Dunkerton 1990). For both methods we find that while the number of transitions in a single month can be a chance occurrence, the total number of transitions in three or five consecutive months is highly significant in the NCEP–NCAR and the FUB datasets (but not in the shorter ERA-40 dataset).

The seasonality of the transitions is consistent with the seasonal distribution of bimodality (Fig. 7) so that months dominated by transitions correspond to months with little deviation from bimodality. This adds confidence to our finding of the same seasonality for westerly/easterly and easterly/westerly transitions.

The seasonal distribution of bimodality is different in the two subperiods (Fig. 7, middle and lower panels). The early period (1948–79) resembles the full period with bimodality in the full autumn–winter season. However, in the later period (1980–2008) bimodality begins and ends earlier so that bimodality now is observed in the last half of the calendar year. The weaker bimodality in the 1979–99 period of the extended winter QBO as described in sections 4 and 6 is therefore a consequence of this seasonal shift in the bimodality. Together with the results in section 5 regarding the influence of the bimodality of the QBO on the vortex, this is consistent with the suggestion by Anstey and Shepherd (2008) that the low-frequency variability of the Holton–Tan relationship described in Lu et al. (2008) is related to changes in the seasonality of the QBO.

8. Conclusions

We have investigated the QBO and its relation to the NH winter vortex. Our study complements earlier work as we have focused on the connection between the bimodality of the QBO and the previous reported bimodality of the vortex. We have studied the QBO and the vortex derived from three different datasets. The vortex was identified as the leading PC of the geopotential height north of 20°N at 20 hPa. The QBO was described by the zonal-mean zonal wind at the equator at 50 hPa.

Our major conclusions are as follows:

- Considering the whole period the winter mean QBO shows a significant bimodality at 50 hPa. Bimodality is apparent in the altitude interval between 70 and 8 hPa. The significance also holds when the strong negative autocorrelations between consecutive winters are considered.
- The bimodality previously reported in the stratospheric NH winter vortex (Christiansen 2003) is strongly connected to the bimodality of the QBO. Both series show a concurrent shift in 1979; the shift in the vortex is from the weak to the strong phase and the shift in the QBO is from a period of strong bimodality to a period of weaker or no bimodality. These observations are in accordance with the sign of the Holton–Tan relationship.
The abnormal period 1979–99 with little bimodality in the QBO—and with a weak Holton–Tan relationship (Lu et al. 2008)—can be a chance occurrence. The shift observed in the winter vortex in 1979 may be a consequence of the random change in the QBO. No additional physical explanation of the shift of the vortex may be necessary, as speculated in Anstey and Shepherd (2008).

The seasonal distribution of the QBO (Fig. 7) shows a more bimodal structure in the last half of the year than in the first half. This is significant when compared to surrogate time series constructed to have the same distributions of periods as the QBO. Only 2% of the surrogates show as large deviations from unimodality in any consecutive 5-month period as the observed QBO in August–December. Thus, the seasonal inhomogeneity

**FIG. 10.** Seasonality of the QBO phase transitions at 50 hPa, showing (left) westerly/easterly and (right) easterly/westerly transitions for (top) ERA-40, (middle) NCEP–NCAR, and (bottom) FUB data. The annual cycle and variability faster than 6 months were removed before the transitions were determined. The years of the transitions are also indicated.

- The abnormal period 1979–99 with little bimodality in the QBO—and with a weak Holton–Tan relationship (Lu et al. 2008)—can be a chance occurrence. The shift observed in the winter vortex in 1979 may be a consequence of the random change in the QBO. No additional physical explanation of the shift of the vortex may be necessary, as speculated in Anstey and Shepherd (2008).

- The seasonal distribution of the QBO (Fig. 7) shows a more bimodal structure in the last half of the year than in the first half. This is significant when compared to surrogate time series constructed to have the same distributions of periods as the QBO. Only 2% of the surrogates show as large deviations from unimodality in any consecutive 5-month period as the observed QBO in August–December. Thus, the seasonal inhomogeneity

**TABLE 3.** Statistical significance of the seasonal clustering of the QBO phase transitions. The statistic is the maximum number of transitions in five or three consecutive months or in a single month. The surrogates are generated either by drawing the transitions randomly with equal probability for each month or by drawing the QBO periods randomly from the observed distribution (bold numbers).

<table>
<thead>
<tr>
<th></th>
<th>Westerly/easterly</th>
<th>Easterly/westerly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 months</td>
<td>3 months</td>
</tr>
<tr>
<td>ERA-40</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>NCEP–NCAR</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>FUB</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
shown in (Fig. 7) is indicative of the QBO being locked to the annual cycle.

- The previous point is consistent with the easterly/westerly and westerly/easterly transitions (Fig. 10) of the QBO, which peak in May–June with very few transitions in the later half of the year. In agreement with Baldwin et al. (2001) and Pascoe et al. (2005) but in disagreement with Dunkerton (1990) and Hampson and Haynes (2006), we find the same seasonality in easterly/westerly and westerly/easterly transitions. The seasonality of the transitions is strongly statistically significant in both the NCEP-NCAR and the FUB datasets but not in the ERA-40 dataset.

Finally, we reiterate that the decadal variability of the QBO and the vortex may be a consequence of the combination of higher frequencies. Here, the annual cycle combines with the quasi-periodicity of the equatorial QBO. In Christiansen (2000) low frequencies in the extratropics were generated in a simple model by combinations of the annual cycle and intraannual time scales related to the downward propagation of anomalies. Such examples remind us that low-frequency variability does not necessarily require external forcings or physical components with long characteristic time scales.

Acknowledgments. This work was supported by the Danish Climate Centre at the Danish Meteorological Institute. The NCEP-NCAR Reanalysis data were provided by the NOAA–CERES Climate Diagnostics Center, Boulder, Colorado, from their Web site (http://www.cdc.noaa.gov/). The ERA-40 data were provided by European Centre for Medium-Range Weather Forecasts. The FUB QBO indices were obtained online (http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html), as were the geopotential heights (http://www.sparc.sunysb.edu/html/fubobs.html).

REFERENCES


