NOTES AND CORRESPONDENCE

A Look at the Recently Proposed Solar–QBO–Weather Relationship

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ABSTRACT

Surface meteorological data at several stations over the period 1875–1936 are examined in relation to solar activity. In particular an attempt is made to see if these historical data can be reconciled with the sun–QBO–weather relationship recently found in modern (post-1950) data by van Loon and Labitzke (vLL). The basic problem in extending vLL's analysis to earlier periods is ignorance of the phase of the QBO. In the present study, vLL's computations are repeated for the historical data using several million possible sequences for the phase of the QBO. The results reveal problems in reproducing vLL's results in the earlier data. This indicates either that the QBO behaved differently in the past, or that vLL's results for a solar–weather relationship are not stable over the long term.

1. Introduction

Labitzke (1987), Labitzke and van Loon (1988), and van Loon and Labitzke (1988; hereafter vLL) presented evidence that the Northern Hemisphere winter weather is significantly affected by a subtle combination of the tropical stratospheric quasi-biennial oscillation (QBO) and the 11-year solar activity cycle. For example, they find *that when only winters with a westerly tropical QBO phase are considered,* a strong positive correlation exists between solar activity and sea level pressure (SLP) over northern Canada and Greenland. vLL showed that strong correlations between solar activity and the tropospheric temperature and pressure in other regions also appear when the data are stratified by the QBO phase. Their results are based on data spanning about 3.5 solar cycles. Given the difficulty of accounting for these findings with the current understanding of atmospheric dynamics, the claims of vLL are likely to be controversial. The literature is replete with other examples of apparent solar-terrestrial correlations that have broken down after a few solar cycle periods (e.g., Pittock 1978). A final resolution of the issues raised by Labitzke and van Loon's work will probably await the acquisition of more data over the next few decades.

The data analysis in vLL was limited to the period when the QBO phase could be determined from routine tropical stratospheric wind observations (i.e., since 1952). The present paper considers how well earlier tropospheric data can be reconciled with the vLL solar–weather connection. In the absence of direct observations of the stratospheric QBO during this earlier period, the present analysis will use ensembles of hypothetically possible sequences of QBO phases.

2. Data

The analysis described below requires time series of yearly values of solar activity and surface pressure and temperature. Following vLL all of these were chosen as January–February means. The solar activity was estimated using the monthly "Zurich" sunspot numbers reported in Waldemeier (1961). This quantity tends to follow quite closely the 10.7 cm solar radio flux used by vLL. It is also of interest to note that when Labitzke and van Loon's analysis for North Pole 50 mb temperatures is repeated using sunspot number as the index of solar activity, the correlation is actually slightly larger (see Labitzke 1987).

The meteorological data are from stations chosen for their location near the maximum surface pressure or temperature correlations found by vLL. In particular, vLL found correlations in the westerly QBO phase of something over +0.7 between solar activity and SLP in northwestern Greenland (see Fig. 3a of vLL). The present study uses SLP data for two stations in this area: Upernivik (72°47′N, 56°7′W) and Jacobshavn (69°13′N, 51°2′W). In southern California vLL found large negative correlations (less than −0.6) between solar activity and SLP during the easterly QBO phases (see Fig. 3b of vLL). In the present study station surface pressure at San Diego (32°43′N, 117°10′W) is employed. vLL found surface air temperature at Charleston, South Carolina, has a −0.69 correlation with solar activity when only westerly QBO phases are considered.

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TABLE 1. Values of solar and meteorological data used in the analysis. Each value is a mean of January and February. Values for Upernivik and Jacobshavn are SLP in mb. For San Diego values are for station pressure in mb. At Charleston the values are surface temperature in °C. In some cases these values have been converted from the units used in the original sources.

Year	Sunspots	Upernivik	Jacobshavn	San Diego	Charleston
1875	18.05	1007.45	1005.72	1007.46	8.50
1876	14.65	1006.25	1004.05	1008.20	12.31
1877	16.55	1001.52	1000.45	1006.62	9.97
1878	4.95	1006.45	1003.78	1006.46	10.00
1879	0.80	1007.38	1003.92	1007.26	9.33
1880	25.60	1004.38	1004.32	1008.19	13.72
1881	44.80	1017.45	1016.72	1007.93	9.28
1882	57.25	1006.32	1004.78	1006.64	13.08
1883	53.57	996.45	994.65	1007.45	11.97
1884	89.20	1004.45	1003.05	1006.27	11.11
1885	57.30	1010.72	1008.65	1006.29	9.14
1886	27.90	1011.72	1010.85	1005.11	7.36
1887	11.75	1001.58	998.85	1006.84	10.67
1888	9.90	1014.05	1004.85	1006.86	11.42
1889	4.65	1009.32	1007.52	1005.63	9.47
1890	2.95	1000.92	1000.18	1007.68	15.28
1891	17.85	1007.25	1006.72	1006.27	12.22
1892	72.35	1016.65	1016.18	1005.51	9.97
1893	74.00	1009.18	1007.58	1006.30	9.50
1894	83.90	1002.98	999.92	1009.35	11.31
1895	65.25	1014.38	1012.92	1006.07	7.00
1896	43.20	1010.12	1009.12	1006.52	9.92
1897	35.00	1013.18	1012.65	1006.14	10.42
1898	33.30	1010.92	1009.30	1006.96	11.14
1899	14.35	1007.32	1005.18	1006.98	9.50
1900	11.50	1012.58	1010.52	1005.93	9.47
1901	1.30	1008.98	1006.78	1005.67	9.03
1902	2.75	1013.32	1010.12	1006.84	7.42
1903	12.65	998.45	994.32	1006.54	10.39
1904	28.05	1004.98	1002.32	1007.40	8.25
1905	70.30	1007.52	1006.12	1004.73	7.19
1906	38.40	1006.98	1000.85	1006.69	9.94
1907	92.30	1006.12	1002.05	1006.57	11.58
1908	36.55	1006.18	1001.78	1007.03	9.17
1909	51.65	1006.78	1001.98	1007.56	12.14
1910	28.95	1007.05	1005.05	1008.82	9.31
1911	6.20	1004.38	1001.72	1007.28	12.03
1912	0.15	1008.65	1004.45	1006.69	7.53
1913	2.60	998.65	995.18	1007.11	13.17
1914	2.70	1004.12	999.78	1006.91	9.36
1915	32.65	1012.98	1009.65	1005.58	10.08
1916	50.35	1002.72	999.12	1006.94	11.94
1917	73.30	999.78	998.58	1008.59	11.25
1918	80.65	1010.38	1007.18	1006.52	9.08
1919	63.80	1012.92	1010.05	1007.46	10.50
1920	52.50	1006.12	1004.32	1006.88	9.53
1921	29.90	1005.72	1001.78	1007.85	11.25
1922	19.10	1005.58	1002.45	1006.83	10.81
1923	3.00	1006.98	1003.38	1006.61	10.86
1924	2.80	1007.58	1003.32	1008.02	9.31
1925	14.35	1006.32	1003.78	1007.78	11.47
1926	70.85	1000.38	997.78	1007.33	10.19
1927	87.30	1004.05	998.52	1007.36	12.75
1928	78.50	995.05	989.85	1008.19	9.89
1929	65.85	1007.52	1003.05	1006.37	10.89
1930	57.60	1001.38	994.78	1006.19	11.67
1931	28.85	1008.18	1003.58	1005.20	9.97
1932	11.35	1002.58	998.85	1006.84	15.31
1933	17.25	1005.85	1001.92	1007.25	12.42
1934	5.60	1003.92	997.92	1008.29	9.36
1935	19.55	1003.52	998.25	1007.30	10.47
1936	68.55	1014.52	1011.52	1005.90	8.50

The present study also uses the surface air temperature at Charleston (32°47′N, 79°56′W).

The monthly mean pressure and temperature at these stations are taken from the "World Weather Records" published by the Smithsonian Institution. Temperature data for Charleston and station pressure at San Diego are available from 1873, but the SLP data at Jacobshavn and Upernivik start in 1874 and 1875, respectively. The data records at the two Greenland stations both stop after 1936. Thus the analysis described below is limited to the period 1875–1936 when data from all four stations are available. The only exceptions are January–February 1888 and January 1889 when data at Jacobshavn are missing, and January–February 1927 when data at Upernivik are missing. In these cases the missing values are replaced with long-term means. The values of all the solar and terrestrial variables in each winter are given in Table 1.

3. Indications of QBO phase in the pre-1950 period

Van Loon and Labitzke classified every winter as being either easterly (E) or westerly (W), depending on the sign of the January equatorial wind averaged at 40 and 50 mb. The only direct observations of the tropical stratospheric wind prior to about 1950 appear to be a few balloon ascents during 1909–19 in Indonesia and in 1908 in east Africa (e.g., Ebdon 1963). While only a relatively small number of ascents actually reached the lower stratosphere, Ebdon felt he could estimate the times of E and W phase at the 19.5 km level (roughly 60 mb) from 1908 to 1918. Assuming that the QBO wind evolution was similar to that observed today, the 40–50 mb transitions from E to W may be taken as occurring a month or two earlier. The E regime descends more slowly, and so the 40–50 mb transitions might be taken about three months earlier than those at 60 mb. Using Ebdon's results (his Table 4) in this way, one concludes that vLL would likely have classified the Januaries of 1909, 1911, 1913, 1915, and 1917 as W, and the Januaries of 1910, 1912, 1914, 1916, and 1918 as E. In addition the motion of the dust cloud following the eruption of Mount Krakatoa in August, 1883, suggests that the lower stratosphere was near the extreme easterly phase of the QBO at that time (e.g., Wexler 1951). This does not give a definite indication of the January phase, but suggests that January 1883 and January 1884 were probably not *both* W.

TABLE 2. Correlation of meteorological variables with sunspot number using all years (regardless of QBO phase).

Station	Variable	Correlation 1875–1914	Correlation 1897–1936
Upernivik	SLP	0.11	−0.08
Jacobshavn	SLP	0.16	−0.08
San Diego	Pressure	−0.05	−0.06
Charleston	Temperature	−0.01	0.06

TABLE 3. Summary of "best possible" single station results for different variables when only one phase of synthetic QBO phases is included in the calculation. Also shown are best results when the QBO series are constrained by observations.

Station	Variable	Period	Max (or min) simulated correlation	With constraint	vLL value
Upernivik	SLP	1875–1914	0.76	0.74	>0.7
Upernivik	SLP	1897–1936	0.50	0.31	>0.7
Jacobshavn	SLP	1875–1914	0.72	0.68	>0.7
Jacobshavn	SLP	1897–1936	0.48	0.33	>0.7
San Diego	Pressure	1875–1914	−0.82	−0.64	<−0.60
San Diego	Pressure	1897–1936	−0.67	−0.32	<−0.60
Charleston	Temperature	1875–1914	−0.70	−0.64	−0.69
Charleston	Temperature	1897–1936	−0.75	−0.54	−0.69

4. Analysis

In view of the fragmentary nature of the QBO record prior to 1950, the present paper considers whether the pre-1950 surface meteorological and sunspot data can be reconciled with vLL's results for *any plausible sequence of QBO phases.*

The first step in this analysis was the construction of possible series of QBO phases for earlier periods. Following vLL it is assumed that each winter can be assigned as either E or W. In the modern record three consecutive winters of the same phase are never seen, nor are two E(W) winters ever followed by two W(E) winters. When these "rules" are applied, it turns out that there are 7 828 976 different QBO series possible over any 40-year period. The number of possibilities naturally rises rapidly with the length of period considered. Practical considerations limited the present analysis to 40-year periods. This is also comparable to the 35 years used by vLL.

After the 7 828 976 possible sequences were generated, the correlation coefficient between series of sunspot numbers and station pressure (or SLP) and temperature data were computed separately for the W and E phases in each possible sequence. This was done for two overlapping 40-year periods, 1875–1914 and 1897–1936.

The computation of correlation coefficients was repeated for all of the possible QBO time series that satisfied the "rules" given above *and* that agreed with Ebdon's results for 1909–18 and were consistent with the Krakatoa winds in 1883–84. This allows a total of 164 862 possibilities for 1897–1936 and 522 724 possibilities for 1875–1914.

The question remains whether the actual sequence of QBO phases in 1875–1914 or 1897–1936 is indeed captured in one of the millions of possibilities generated by the application of the "rules" mentioned above. Current understanding of the theory of the QBO does not allow any serious evaluation of the probabilities that one of the "rules" might be violated. Nor is there any obvious statistical extrapolation of the limited data available. This issue is discussed more fully in appendix A. In light of that discussion it seems likely that the most probable violation of the "rules" would be the occurrence of three W Januaries in a row. The generation of the 40-year QBO sequences was repeated allowing *one* occurrence of three consecutive W phases (but not allowing more than one E year to follow). When this generalization is included the number of possibilities for any 40-year period rises to 29 739 174. Many of the computations of correlation coefficients were repeated for this larger, less restrictive set of possibilities.

TABLE 4. Results for the 1875–1914 period when pressure data at both Upernivik and San Diego are considered together.

Correlations for W phases at Upernivik	Number of cases	Minimum correlation for E phases at San Diego
>0.7	146	0.01
>0.65	942	−0.04
>0.60	2346	−0.06
>0.55	4626	−0.10
>0.50	10 896	−0.18
>0.45	23 104	−0.26

5. Results

Table 2 shows the correlation coefficients computed between the sunspot number (SSN) and the meteorological series when *all* years of each 40-year period are considered. These correlations are all very small, in agreement with vLL's findings.

The first line of Table 3 shows the maximum correlation obtained between SSN and Upernivik SLP for the W phases as chosen from any of the 7 828 976 plausible QBO series for 1875–1914. In this case the maximum correlation obtainable is 0.76. This demonstrates that it is possible that this aspect of the vLL results could have held during 1875–1914.

The remaining lines in Table 3 give similar results for all the four stations and for both 1875–1914 and 1897–1936. Note that for San Diego pressure (Charleston temperature), the results quoted are for the *most negative* correlations obtainable when only years with E (W) QBO phase are considered.

The fifth column in Table 3 gives the best possible results among the 164 862 QBO series for 1897–1936 that agree with Ebdon and the 522 724 series for 1875–1914 constrained to agree with Ebdon and the Krakatoa winds.

For 1875–1914 there is no difficulty reconciling these results with vLL's findings. It seems possible to find at

TABLE 5. As in Table 4, but for 1897–1936.

Correlations for W phases at Upernivik	Number of cases	Minimum correlation for E phases at San Diego
>0.45	561	−0.08

least some plausible QBO time series that would allow vLL's solar–QBO–weather relationship to be reproduced.

The results for 1897–1936, however, are less reassuring. Consider the Greenland SLP results for 1897–1936. Here the maximum possible correlations of 0.50 at Upernivik and 0.48 at Jacobshavn are lower than the roughly 0.7 found in modern data by vLL. When only those QBO series that agree with Ebdon are considered, the discrepancy with the modern results becomes even more serious (only 0.31 at Upernivik and 0.33 at Jacobshavn).

The findings shown in Table 3 suggest that if vLL's analysis could be applied to 1897–1936, some of their results would not duplicate those found for 1952–87; however, this lack of stability in the results has to be interpreted with caution. Even if one assumes that the effect found by vLL is real, then their 35-year sample (or the present 40-year period) is not large enough to give perfectly stable estimates of the correlation coefficients. vLL used a bootstrap technique to estimate the possible error in their estimates of correlation coefficients (see the Appendix in vLL). Their results (see, for example, the fourth line in their Table 5) suggest that the Greenland pressure correlation they obtained should be regarded as having a possible sampling error of the order of ±0.2. Thus the results given in the fourth column of the present Table 3 may in fact be reconcilable with those of vLL. On the other hand, the discrepancy between the 0.31 and 0.33 correlations for Upernivik and Jacobshavn in the sixth column of Table 3 and the 0.7 found by vLL is disconcerting. If Ebdon's identification of QBO phases is correct, then there would be serious difficulty in reconciling the data in 1897–1936 with vLL's modern results.

The computation of the correlation between SSN and Jacobshavn SLP for 1897–1936 was repeated allowing one occurrence of three consecutive W phases but constrained to agree with Ebdon's results during 1909–18. This produces 551 694 possibilities. The highest attainable correlation rose only very slightly to 0.34.

A more demanding test of vLL's proposed relationship would be one that required both the strong positive correlations of SSN with Greenland SLP in the W phases *and* the strong negative correlation between SSN and San Diego pressure in the corresponding E phases. Table 4 summarizes the result of such a test, in this case applied to Upernivik SLP during 1875–1914. The first step in this analysis was picking all the QBO series that produced W phase correlations of SSN and SLP greater than some threshold. Thus, for example, 146 different QBO series lead to W phase SSN–SLP correlations greater than 0.7. Then the correlation between SSN and San Diego pressure was computed for the E phases of each of these 146 QBO possibilities. The third column in Table 4 shows the minimum correlation with San Diego pressure found for any of these. These numbers should be compared to the roughly −0.60 obtained by vLL in modern data. It is seen that the San Diego results in the 1875–1914 data never approach this, even when a rather low threshold of 0.45 is used with the Upernivik W phase correlation. The results are very similar when Jacobshavn SLP is used (not shown) or when the 1897–1936 period is considered (Table 5).

Tables 6 and 7 summarize the results of a similar analysis using Charleston temperature and San Diego pressure. Here the possible QBO series are picked by requiring that the W phase SSN–Charleston temperature correlation be less than (i.e., more negative than) some threshold. Once again, even when a rather weak threshold is used for the W phase correlation, the SSN–San Diego pressure correlation over the corresponding E phases never approaches −0.6.

Tables 8–11 show the results of the various two station analyses repeated using the 29 739 174 QBO series that allow one occurrence of three consecutive W years. The more liberal selection of possibilities produces possible results somewhat closer to those of vLL, but the improvement in agreement is generally modest. Thus, for example, of those 1875–1914 series that pro-

TABLE 6. Results for the 1875–1914 period when temperature data at Charleston and pressure data at San Diego are considered together.

Correlations for W phases at Charleston	Number of cases	Minimum correlation for E phases at San Diego
<−0.65	206	0.10
<−0.60	1058	−0.02
<−0.55	3660	−0.05
<−0.50	8916	−0.15
<−0.45	18 036	−0.23

TABLE 7. As in Table 6, but for 1897–1936.

Correlations for W phases at Charleston	Number of cases	Minimum correlation for E phases at San Diego
<−0.65	275	−0.13
<−0.60	955	−0.19
<−0.55	2667	−0.24
<−0.50	6083	−0.34
<−0.45	10 948	−0.40

TABLE 8. As in Table 4, but for 29 739 174 possibilities generated by the less restrictive QBO rules.

Correlations for W phases at Upernivik	Number of cases	Minimum correlation for E phases at San Diego
>0.75	9	0.04
>0.7	645	0.00
>0.65	7863	−0.04
>0.60	30 772	−0.08
>0.55	84 007	−0.18
>0.50	210 760	−0.22
>0.45	495 534	−0.30

TABLE 9. As in Table 5, but for 29 739 174 possibilities generated by the less restrictive QBO rules.

Correlations for W phases at Upernivik	Number of cases	Minimum correlation for E phases at San Diego
>0.50	101	−0.03
>0.45	7598	−0.14

duce W phase SLP correlations at Upernivik greater than 0.6, the minimum correlation with E phase SLP at San Diego is −0.06 with the basic rules and −0.08 with the generalized rules (Table 8).

The results in Table 9 show that the more liberal rules allow one to find 101 QBO series that produce W phase correlations at Upernivik greater than 0.50 (as opposed to none with the basic rules); the smallest E phase correlation at San Diego for these series is −0.03. Tables 10 and 11 document a similarly small improvement in the Charleston plus San Diego results over those obtained with the "basic" rules (Tables 6 and 7).

The discrepancies between the "best possible" results one can obtain with the historical data and the modern results suggest that vLL's findings are not stable with time. Some differences between the 40-year periods analyzed here and the 35 years considered by vLL would be expected just from sampling error. The values given in Tables 4–11, however, show there is difficulty in *even roughly approximating* vLL's modern results at two sites simultaneously.

There remain important issues in interpreting this apparent lack of stability of vLL's results. The skeptical conclusion would be that the post-1952 results were simply fortuitous, but vLL's results may reflect some real physical mechanism, and the operation of that mechanism may have altered significantly with time. There are two interesting points to note concerning this last possibility. One is that the 11-year cycle of solar activity itself seems to undergo a longer period modulation. The last few decades have been characterized by strong sunspot cycles relative to those in the late nineteenth and early twentieth centuries (e.g., Waldemeier 1961).

The other point is that the patterns of interannual variability of tropospheric circulation may have changed during the twentieth century. In particular, van Loon and Madden (1983) showed that the interannual variability of January mean SLP in the North Atlantic was considerably smaller during 1901–16 than during the entire 1901–80 period. This change was most pronounced over Greenland.

TABLE 10. As in Table 6, but for 29 739 174 possibilities generated by the less restrictive QBO rules.

Correlations for W phases at Charleston	Number of cases	Minimum correlation for E phases at San Diego
<−0.70	4	0.17
<−0.65	931	0.10
<−0.60	6750	−0.02
<−0.55	32 357	−0.11
<−0.50	109 380	−0.24
<−0.45	287 060	−0.28

TABLE 11. As in Table 7, but for 29 739 174 possibilities generated by the less restrictive QBO rules.

Correlations for W phases at Charleston	Number of cases	Minimum correlation for E phases at San Diego
<−0.70	182	−0.07
<−0.65	1216	−0.13
<−0.60	6062	−0.19
<−0.55	23 894	−0.24
<−0.50	72 406	−0.34
<−0.45	180 044	−0.40

6. Conclusion

If the phase of the tropical QBO were known for each winter, it would be a very straightforward matter to test vLL's surface pressure results in historical data. One would simply compute correlations of SSN with SLP for all the W phases and then for all the E phases. The results could then be compared to vLL's comparable calculations for modern data (i.e., their Figs. 3a and 3b). Similarly, the historical surface temperature data could be stratified by QBO phase and then correlated with SSN. The results could then be compared with vLL's modern data (their Figs. 8 and 10).

Unfortunately, one cannot reliably determine the QBO phases before 1950 (except possibly during 1909–18). The approach adopted in this paper was to repeat vLL's analysis for *all* plausible time series of QBO phases and see if *even a single one of these* could allow vLL's results to be duplicated. The results given in Tables 3–7 show that, if the QBO phases during 1875–1936 followed the same pattern as in modern observations, no reproduction of vLL's results seems possible. This problem becomes even worse if Ebdon's (1963) identification of QBO phases from 1909–18 is correct. Thus one is forced to conclude that either (i) the QBO behaved somewhat differently in the past, or (ii) that vLL's solar-terrestrial relationship is not a stable feature of the data. In the latter case, one would expect that as more data are collected over the next few decades, vLL's tropospheric correlations will start to break down—or at least change in some substantial way. Similarly, if the QBO behavior is really more variable than the available post-1950 data suggest, one would hope to see direct evidence of this over the next few decades.

APPENDIX A

Timing of QBO Transitions

Since the advent of regular wind soundings of the tropical stratosphere in the early 1950s, detailed data have been collected on roughly 15 QBO cycles. These data reveal a fairly regular oscillation but with some variability in the duration of both the east and west phases. The critical issue for the present study is to determine the range of plausible variability over a 40-year period. In practice this amounts to establishing a set of "rules" for allowable sequences of E and W phases. Hopefully the rules will be liberal enough so that it would be extremely improbable that the actual QBO sequence would violate them during a 40-year period.

Figure 1 of Naujokat (1986) was examined to determine the timing of E and W phase transitions for the period 1954–85. At 45 mb it appears that the beginning of E phases (i.e., the first month that is clearly E) can be identified as 3/54, 5/56, 7/58, 6/60, 8/62, 7/65, 4/68, 5/70, 7/72, 6/74, 12/76, 6/79, 7/81, and 12/83. The beginning of W phases are 2/55, 5/57, 7/59, 5/61, 10/63, 6/66, 5/69, 5/71, 4/73, 7/75, 12/77, 6/80, 10/82, and 3/85. From these dates one can construct the present Fig. A1, which shows the length of duration of E and W phases in histogram form. The difficulty in quantifying the probability of any unusual situation is apparent from this figure. The distribution of duration is rather irregular, and it is hard to know (for example) how frequently a 25-month long W phase might occur.

The problem of characterizing QBO variability is even more difficult than indicated in Fig. A1. The duration of a particular W phase may depend on the duration of the preceeding E phase. Also the duration of QBO phases seems coupled to the annual cycle in a significant manner. In particular, Holton and Tan (1980) noticed that the equatorial wind at 50 mb was usually clearly E or W in January, i.e., transitions from E to W (or vice versa) tend not to occur near January. vLL also noticed the same phenomenon and used this as a justification for using 40–50 mb winds to stratify winters into E and W QBO phases.

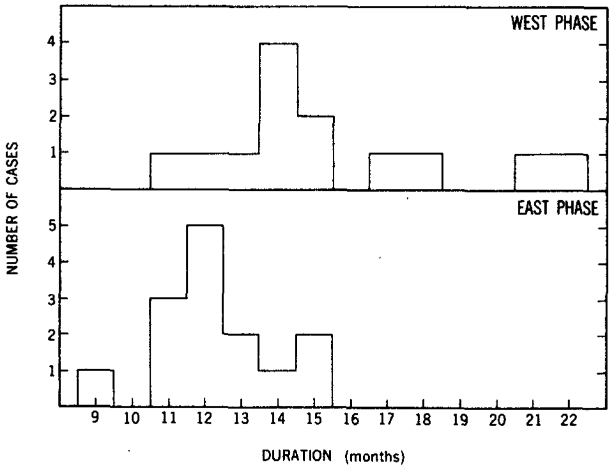

FIG. A1. Histogram showing the length of duration in months of westerly QBO phases (top) and easterly QBO phases (bottom), using the 45 mb winds of Naujokat (1986).

The apparent synchronization of the QBO transitions with the annual cycle make unusual sequences of E and W Januaries even more unlikely. Let us suppose, for example, that a 25-month W phase occurs during any 40-year period with probability p. The only way this could lead to three W Januaries in a row is if the phase both began and ended in January. This would require two transitions in NH winter and would presumably have a probability of occurrence considerably less than $p/12$. Similarly, while there might be occasional 11-month E phases, the likelihood that they would extend from February to December (and thus possibly producing 3 W Januaries in a row) would presumably be very small.

These arguments give one confidence that violations of the basic "rule" of allowing at most two successive E or W Januaries will be unlikely, but it does not seem possible to quantify the actual probability. In these circumstances the approach adopted in this paper was to repeat the analyses allowing one violation of the simple rules during a 40-year period. The most plausible violation seemed to be the occurrence of three W Januaries in a row. This could be either due to a very long W phase, or a very short E phase. The occurrence of three successive E Januaries seemed so unlikely that this possibility was not considered.

APPENDIX B

Some Additional Calculations

Many of the calculations described in section 5 were repeated under slightly different conditions. For example, Waldemeier (1961) gives, in addition to the monthly mean SSN, a monthly value of "smoothed" sunspot number (essentially a one-year running mean). Because the unsmoothed monthly SSN are a little noisy, it is possible that the smoothed SSN are a better index of solar activity. When the calculations are repeated using the smoothed SSN, the results for the "best" correlation coefficients in Tables 3–7 change very little (typically of the order of ±0.02).

An unrelated concern is with the synthetic QBO series. All of the 7 828 976 40-year series are realistic, in that no 4-year periods appear, but many of them have other abnormal features (at least as judged from modern QBO behavior). Thus, vLL's analysis of the modern record suggests that more winters will be classed as W than E (19 W's vs 17 E's during 1952–87 despite both end years being E). This seems to reflect the basic behavior of the QBO wind oscillation. [More time is spent near the extreme W phase than near the extreme E phase: see Fig. 9 of Hamilton (1984), or Fig. 10.15 of Newell et al. (1974).] Many of the calculations reported in the main body of the paper were repeated with an additional constraint that the number of W phases over 40 years had to be at least 20. Other constraints (e.g., requiring that the mean QBO period over 40 years be reasonably close to the "modern" value of 27 months) were also imposed in some further calculations. All these additional requirements had the effect of making the "best" correlation coefficients more difficult to reconcile with vLL's findings; however, the changes in the results from those given in Tables 3–7 were typically quite small (again of the order of 0.02).

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