NOTES AND CORRESPONDENCE

An Examination of Observed Southern Oscillation Effects in the Northern Hemisphere Stratosphere

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ABSTRACT

The effects of the Southern Oscillation on the December–February mean circulation in the Northern Hemisphere stratosphere were investigated using 34 years of data. No evidence for a significant relation between the Southern Oscillation (SO) and the zonally averaged flow is found for any region poleward of 20°N. The effects of the tropical quasi-biennial oscillation (QBO) on the zonal mean flow are much stronger, and this complicates the detection of SO effects. Some more suggestive results are evident when hemispheric maps of height anomalies at 50 or 30 mb are composited for the warm extremes of the SO. The present findings are broadly consistent with earlier suggestions that, on average, the Aleutian high is intensified during the warm extremes of the Southern Oscillation. Even using the 34 years of data now available, however, the statistical significance of this relationship cannot be demonstrated unequivocally. Once again the separation of SO effects from QBO influences in the limited data available is a serious problem.

1. Introduction

The familiar tropical Southern Oscillation (SO) has been demonstrated to have significant effects on the extratropical tropospheric circulation (e.g., Horel and Wallace 1981; van Loon and Madden 1981; Pan and Oort 1983). The possible stratospheric connections with the SO have also been investigated in a number of papers published during the last decade (Wallace and Chang 1982; van Loon et al. 1982; van Loon and Labitzke 1987). Van Loon et al. (1982) examined 15 December–February (DJF) periods and found a tendency for the NH stratospheric vortex to be anomalously weak (strong) during warm (cold) extremes of the SO. This tendency was evident in the zonal-mean geopotential heights. Rather similar results were found by Wallace and Chang (1982). Van Loon and Labitzke (1987, hereafter vLL) studied the same issue using the 28 DJF periods then available (from 1957/58 through 1984/85). With this longer dataset the relationship between the SO and the zonally averaged winter vortex was not so apparent as in the earlier study of van Loon et al. (1982), but vLL identified a tendency for the Aleutian high to be anomalously intense during the warm extremes of the SO. However, vLL noted that the limited data available made it difficult to demonstrate the statistical significance of this result.

The present paper examines SO influences in the NH lower stratosphere using all 34 years of data now available. This reexamination of the stratospheric SO issue is timely since troposphere–stratosphere general circulation models (GCMs) have become sufficiently developed that extensive studies of the sensitivity of simulated stratospheric circulation to imposed sea surface temperature (SST) variations are now possible [in fact, one such study is now underway at GFDL using the "SKYHI" GCM described in Fels et al. (1980)]. The rather systematic changes in SST through the SO cycle provide a nice opportunity to evaluate this aspect of model sensitivity. The present simple data analysis is aimed at providing a useful observational benchmark for such model studies.

2. Data

The data used for this study were monthly mean geopotential heights at 50 and 30 mb originally prepared at the Free University of Berlin from subjectively analyzed daily radiosonde observations. For the present investigation these data were obtained from the widely distributed Greenhouse Effect Detection Experiment (GEDEX) compact disks. The height data for 50 and 30 mb on the GEDEX disks extend from July 1957 through February 1991. This allowed a total of 34 DJF periods to be employed. The data are given on a 10° × 10° latitude–longitude grid from 10° to 90°N. At 10 mb (100 mb) the data are available only for 17 (23) DJF periods.

The present study also made use of the normalized monthly mean SO index (SOI) based on Tahiti and

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TABLE 1. December–February mean SOI for 34 consecutive years.

1957/58	−1.06	1974/75	−0.07
1958/59	−1.09	1975/76	1.42
1959/60	0.14	1976/77	−0.11
1960/61	0.22	1977/78	−1.42
1961/62	1.05	1978/79	−0.05
1962/63	0.28	1979/80	−0.21
1963/64	−0.68	1980/81	−0.14
1964/65	−0.35	1981/82	0.39
1965/66	−0.67	1982/83	−3.05
1966/67	0.63	1983/84	0.13
1967/68	0.16	1984/85	−0.08
1968/69	−0.72	1985/86	−0.10
1969/70	−0.74	1986/87	−1.23
1970/71	1.10	1987/88	−0.50
1971/72	0.35	1988/89	1.03
1972/73	−1.10	1989/90	−1.05
1973/74	1.76	1990/91	−0.01

Darwin surface pressure observations (Allan et al. 1991), also provided on the GEDEX disk. The phase of the QBO was characterized using the monthly mean 50-mb Singapore zonal wind included on the GEDEX disk. The SOI and Singapore winds are available for each of the 34 winters from 1957 through 1991. Table 1 lists the DJF means of this SOI for the 34 years. The SOI is generally at or near its negative extreme during the mature phase of El Niño warmings (e.g., 1957–58, 1972–73, 1982–83).

3. Analysis for zonal-mean geopotentials

Table 2 shows the correlation coefficient of DJF mean SOI with the geopotential height at various pressure levels and latitudes. The boldfaced numbers are those coefficients that are 95% significant in a two-sided *t* test assuming each winter is independent. Poleward of 10°N all the correlations are quite small and none passes the 95% significance test. At 10°N the negative values (statistically significant at 30, 50, and 100 mb) reflect a tendency for the geopotential to be high during the warm phase of the SO. This low-latitude stratospheric result is similar to that found in the troposphere [where the warm Pacific equatorial temperatures drive two tropical anticyclonic circulations, one on each side of the equator; e.g., Horel and Wallace (1981)].

Table 3 shows similar correlations, but now between the geopotential heights and the DJF mean Singapore zonal winds. The correlations in the extratropics in this case are much larger than for the SOI and many of the values pass the 95% significance test. The pattern of positive (negative) correlation equatorward (poleward) of about 60°N appears consistent with the earlier results of Holton and Tan (1980, 1982) and Dunkerton and Baldwin (1991). This pattern of correlation reflects a tendency for the DJF mean zonally averaged westerly vortex to be anomalously weak (intense) during the easterly (westerly) phase of the QBO.

TABLE 2. Correlation coefficients of December–February mean zonally averaged geopotential height with the SOI.

Pressure (mb)	Number of years	Latitude (°N) 10	30	50	70	90
10	17	−0.27	−0.16	0.01	−0.22	−0.26
30	34	**−0.41**	−0.13	0.12	−0.16	−0.17
50	34	**−0.44**	−0.31	0.09	−0.15	−0.16
100	23	**−0.69**	−0.35	0.11	−0.08	0.00

TABLE 3. Correlation coefficients of December–February mean 50-mb zonal wind at Singapore with zonally averaged geopotential height.

Pressure (mb)	Number of years	Latitude (°N) 10	30	50	70	90
10	17	0.12	**0.72**	0.42	−0.46	−0.38
30	34	**0.37**	0.18	0.30	**−0.38**	−0.33
50	34	**0.38**	−0.20	0.17	**−0.37**	−0.31
100	23	−0.12	−0.19	0.04	**−0.41**	**−0.37**

Given the significant relation between the phase of the QBO and the extratropical geopotential, it is natural to ask whether even the small correlations with the SOI in Table 2 might be due to aliasing of the QBO signal. In order to test this possibility, the time series of DJF mean zonally averaged geopotential at each point was filtered by subtracting its least-squares linear fit to the Singapore wind time series. Then the filtered geopotential heights were correlated with the SOI. Table 4 shows the result of this procedure. The negative correlations at 10°N seen in Table 2 are actually stronger when the QBO influence is removed, but poleward of 10° the correlations in Table 4 are generally smaller than those computed using the unfiltered geopotentials. This supports the view that even the weak indications of extratropical SO influence in Table 2 may be spurious.

4. Results for the three-dimensional structure of the winter mean geopotential

The most striking results presented by vLL were maps of the DJF geopotential anomalies composited

TABLE 4. Correlation coefficients of the December–February mean SOI with the zonally averaged geopotential height, which has been filtered to remove the linear fit to the Singapore zonal winds. See text for details.

Pressure (mb)	Number of years	Latitude (°N) 10	30	50	70	90
10	17	−0.31	−0.12	0.04	−0.19	−0.23
30	34	**−0.51**	0.02	0.09	−0.14	−0.14
50	34	**−0.54**	−0.02	0.09	−0.13	−0.14
100	23	**−0.70**	0.02	0.11	−0.10	−0.01

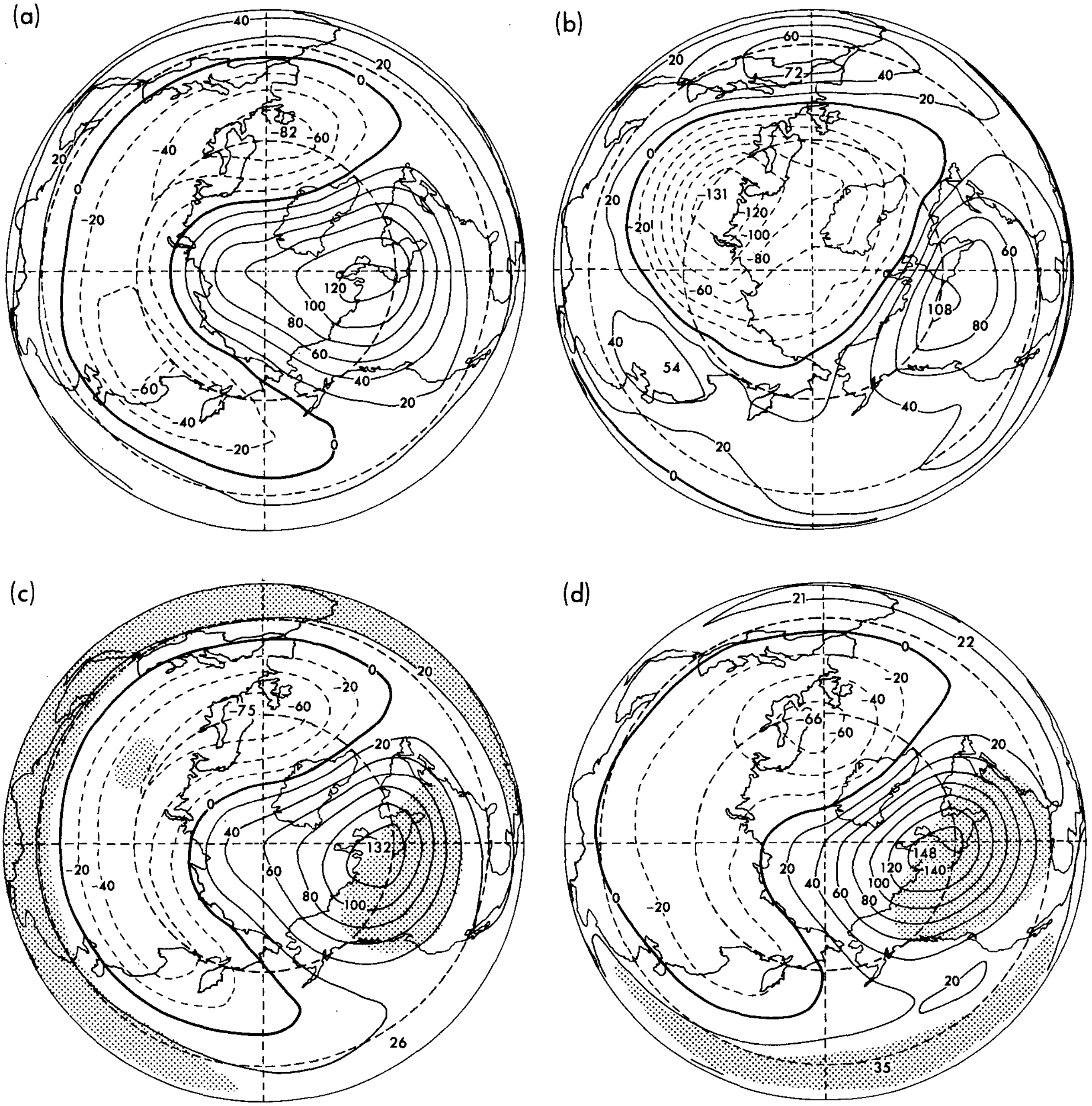

FIG. 1. The difference between the DJF 50-mb geopotential height averaged over "warm" phases of the SO minus the average over the "undisturbed" phases: (a) for the list of "warm" and "undisturbed" winters through 1984/85 given by van Loon and Labitzke, (b) for the warm winters 1986/87 and 1989/90 and all the "undisturbed" winters through 1990/91, (c) for the "warm" winters given by van Loon and Labitzke along with 1986/87 and 1989/90 and the "undisturbed" winters through 1990/91, and (d) for a revised list of "warm" and "undisturbed" winters based solely on the SOI. In each case the contour interval is 20 m and negative values are represented by dashed contours. The shaded areas in panels (c) and (d) are regions where the results are judged significantly different from zero using a 95% criterion in a two-tailed *t* test. The 30° and 60°N latitude circles are shown.

over the warm extremes of the SO. On the basis of tropical Pacific surface data, vLL identified 1957/58, 1963/64, 1965/66, 1969/70, 1972/73, 1976/77, and 1982/83 as "warm" phase SO winters, 1964/65, 1966/67, 1970/71, 1973/74, 1975/76, and 1978/79 as "cold" phase SO winters, while the remaining winters (through 1984/85) were taken as characteristic of the "undisturbed" phase of the SO. Figure 1a shows the mean of the 50-mb geopotential over the "warm" winters minus the average over the "undisturbed" winters (this should reproduce the results in Fig. 2a of vLL). The most obvious feature here is the anomalous high pressure over northern Canada and the corresponding low pressure over the eastern Atlantic and over virtually the entire eastern hemisphere south of 70°N. This figure also makes it clear why the vLL found only a very weak SO signal in the zonal-mean geopotential.

The period since 1984/85 has featured more cycles of the SO. An examination of the SOI time series in Table 1 reveals the winters of 1986/87 and 1989/90 to be warm SO extremes and the winter of 1988/89 to be a cold extreme [evidence for a moderate El Niño in 1986/87 is given in Bergman (1987); evidence for a tropical Pacific warm event in 1989/90 is given in the February 1990 edition of the *Climate Diagnostics Bulletin* issued by the U.S. Climate Analysis Center]. For present purposes the winters 1985/86, 1987/88, and 1990/91 are taken as representative of the "undisturbed" SO phase. Figure 1b shows the 50-mb geopotential averaged over DJF in 1986/87 and 1989/90 minus the mean over all the "undisturbed" winters for the full 34-year period. The overall pattern of anomalously high pressure over northern Canada and low pressure in the eastern hemisphere is found in these two most recent warm phase winters. Thus, it seems that the relation found by vLL has held up during the time since they published their paper. When these two warm events are added to the 7 identified by vLL (and the list of "undisturbed" winters is extended through 1990/91), the resulting 50-mb height anomaly is shown in Fig. 1c (this represents an updated version of Fig. 1a). The general pattern of anomaly found by vLL appears to be confirmed in the updated data. The shaded regions represent grid points where the 9 "warm" winter mean would be judged significantly different from the "undisturbed" mean using a standard 95% two-sided t test (assuming each winter represents an independent sample).

A number of different features of the tropospheric climate (such as rainfall and sea surface temperatures) were used by vLL in their subjective determination of "warm," "cold," and "undisturbed" phases of the SO (see van Loon and Madden 1981; van Loon and Shea 1985 for more details). One could argue that, from the point of view of the stratospheric response, the most direct measure of the tropospheric SO phase might be the Southern Oscillation index (SOI) itself, since it reflects the changes in the large-scale flow pattern. Thus, for example, the winter of 1958/59 is classified by van Loon and Shea (1985) as an "undisturbed" SO winter, since by many measures the major El Niño event of 1957/58 was in retreat. However, the SOI in DJF 1958/59 was still quite low (which was presumably reflected in a pattern of anomalous westerly flow in the lower atmosphere over the tropical Pacific). For present purposes an alternative list of phases was defined by taking the 9 (7) winters with the lowest (highest) values of SOI in Table 1 as the "warm" ("cold") winters. Thus, 1957/58, 1958/59, 1968/69, 1969/70, 1972/73, 1977/78, and 1982/83 replace the 7 winters regarded as "warm" by vLL, and 1961/62, 1966/67, 1970/71, 1973/74, 1975/76, and 1981/82 replace the six "cold" winters of vLL. The composited 50-mb geopotential anomaly for the warm winters computed using this alternate SO chronology is shown in Fig. 1d. The result is not much changed from that using the vLL definitions (Fig. 1c). It is reassuring that the computed SO effects are still present when an objective measure of the SO phase is used as the basis of the composite. It should be noted that still other factors could be used to characterize the phase of the SO (in particular, a referee pointed out that the tropical tropospheric mean temperature typically peaks several months after the minimum in the SOI).

Figure 2 shows the 50-mb geopotential averaged over the 7 cold phase winters minus the average over the 18 "undisturbed" winters. The vLL SO chronology (extended through 1990/91) was used here (results are quite similar when the revised list based on the SOI is used). This represents an updated version of Fig. 6a of vLL. The signature of the cold phase appears as an intensification of the vortex at high latitudes. Unfortunately, this cold phase composite passes the 95% t test only over a very tiny geographical area (in contrast to the corresponding warm phase composite in Fig. 1c). It is also worth noting that the cold phase composite does not resemble the negative of the warm phase anomaly (this was also found by vLL). While this may reflect the complexity of the stratospheric response to the SO, it does mean that the results for the cold SO

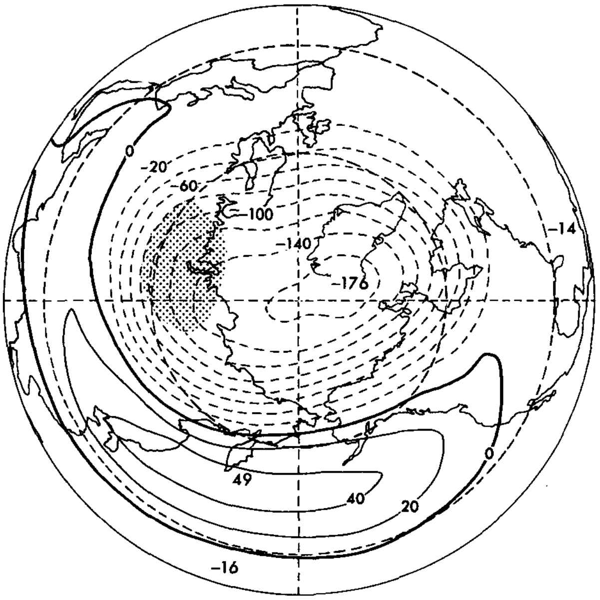

FIG. 2. The difference between the DJF 50-mb geopotential height averaged over "cold" phases of the SO minus the average over the "undisturbed" phases. The years of the "cold" and "undisturbed" phases are taken from van Loon and Labitzke (1987) with an additional "cold" phase in 1988/89. The contour interval is 20 m and negative values are represented by dashed contours. The shaded areas are regions where the results are judged significantly different from zero using a 95% criterion in a two-tailed t test.

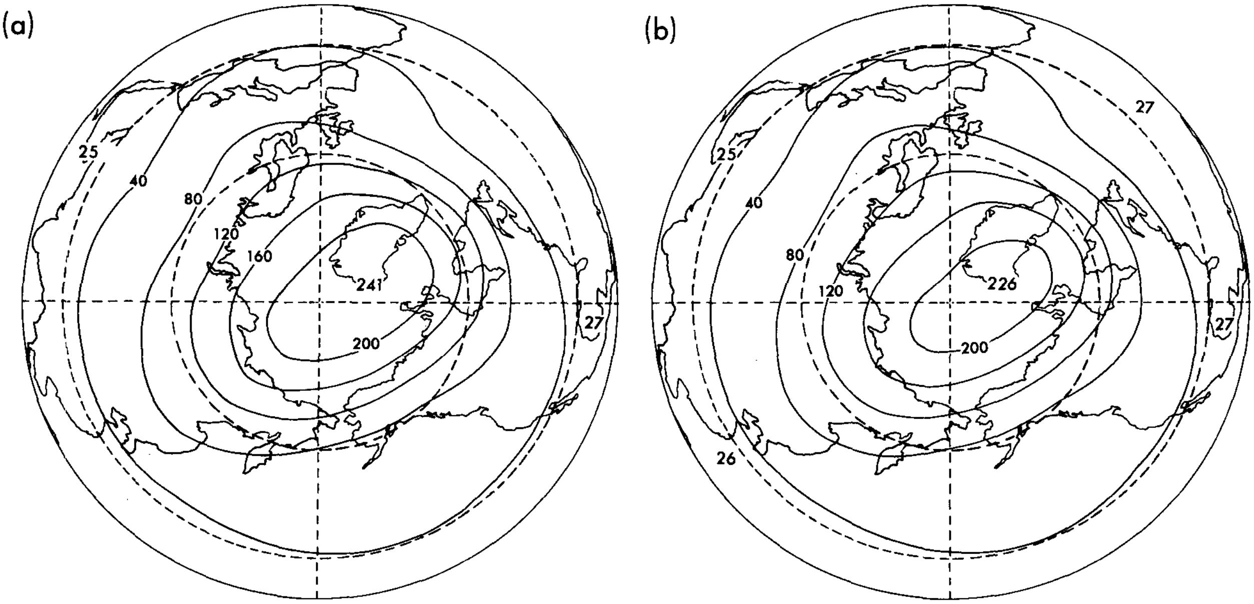

FIG. 3. The standard deviation of the DJF 50-mb geopotential height over the 18 "undisturbed" SO phase winters during the full 34-year period studied (a) for the raw data, and (b) after a linear fit to the Singapore wind time series was removed from the geopotential data. The contour interval is 40 m.

composite cannot add much to the confidence that can be placed in the statistical significance of the warm composite results.

An attempt was made to remove the influence of possible aliasing of QBO signals in the present SO composites. The approach adopted was to compute the least-squares fit of the 34-year time series of DJF geopotential at each grid point to the DJF Singapore zonal winds. This fit was then removed from the original geopotential time series. Figure 3 compares the standard deviation of the DJF mean 50-mb geopotentials in the raw data (panel a) and in the data filtered by removing the fit to the QBO (panel b). Note that this figure includes only those years classed as "undisturbed" (using vLL's chronology extended through 1990/91). The removal of the QBO regression leads to a reduction in the geopotential variance of ~10% over much of the NH. Figure 4 shows the "warm" composite anomaly defined as in Fig. 1c, but computed using the filtered geopotential data. The result has some obvious and substantial differences from that seen in Fig. 1c. Unfortunately in most regions the removal of the QBO signal reduces the magnitude of the mean anomalies more than it reduces the standard deviation of the "undisturbed" winters. As a result, no portion of the hemispheric composite poleward of 20°N in Fig. 4 passes a 95% *t* test. This result demonstrates the difficulty in disentangling QBO and SOI signals even with a 34-year dataset, and it calls into question the validity of the statistical test applied in Fig. 1c (which depends on the independence of the geopotential data in successive winters).

It should be noted that the procedure adopted here for examining SO effects after removing QBO influence represents a test of the following extreme (but physically plausible) question. Start with the assumption that the QBO effects are real (and are well represented by the linear regression with the Singapore winds) and further suppose that any correlation between the SOI and the Singapore winds is purely coincidental. Then can one still find evidence for the SO effects in the geopotential data that stand out clearly above the noise?

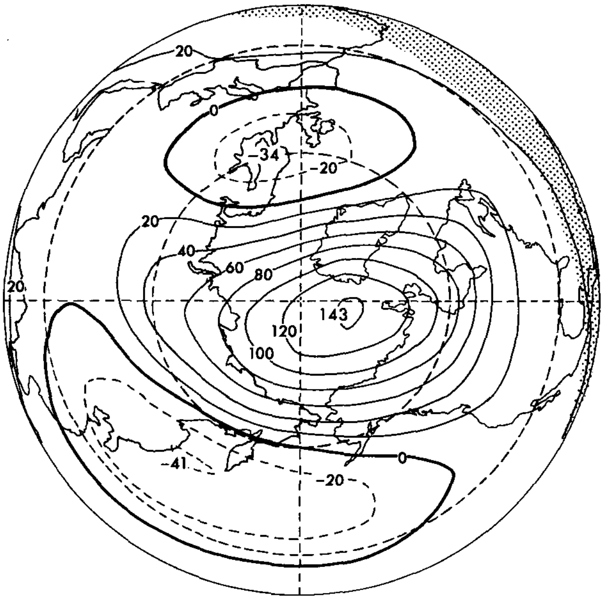

FIG. 4. The mean of the DJF "warm" minus "undisturbed" 50-mb geopotential height composite defined as in Fig. 1c, but using filtered geopotential data that had a linear fit to the Singapore winds removed. The contour interval is 20 m.

A more standard statistical analysis (such as partial correlation) would place the SOI and Singapore winds on an equal footing as possible influences on the 50-mb geopotential, but the present approach represents a more stringent test of the reality of SO effects.

The calculations reported in Figs. 1–4 were repeated using 30-mb geopotentials. The general features of all the 30-mb results are very similar to those seen at 50 mb. In particular, the "warm" phase anomaly pattern in the unfiltered 30-mb data has a fairly large region that would be judged significantly different from the mean using the 95% t test. However, the same anomaly computed using the filtered data has no region poleward of 20°N that passes the t test.

5. Conclusions

The present paper has tried to update earlier analyses of the influence of the SO on the winter mean NH stratospheric circulation. This subject begins with the original finding of van Loon et al. (1982) that the zonal-mean vortex strength depends strongly on the phase of the SO. However, the present results show that when all the currently available data are used, no statistically significant connection can be found between the phase of the SO and the zonally averaged geopotential poleward of 20°N at any level from 100 to 10 mb. This continues the trend seen first in van Loon and Labitzke (1987): that as the available data accumulate, the evidence for SO effects on the zonal-mean extratropical stratospheric circulation becomes increasingly suspect.

By contrast, the results of van Loon and Labitzke (1987) concerning the influence of the SO on the geographical pattern of geopotential in the middle stratosphere are supported by the more recent data now available. In particular, the finding of vLL that, on average, "warm" SO winters have anomalously high pressure over northwestern Canada (accompanied by a croissant-shaped pattern of low pressure in the eastern hemisphere) is characteristic of the two most recent warm extremes of the SO (1986/87 and 1989/90). When these recent data are added to that used by vLL, the resulting "warm" phase DJF composite of heights at 50 mb (or 30 mb) includes large regions that pass a standard t test for significance. This result is robust when a slightly different chronology of the warm and cold extremes of the SO is adopted. However, given the well-known influence of the QBO on extratropical NH winter stratospheric circulation, the assumption needed for the t test of independence of successive winters is not defensible. When a simple approach for removing the QBO influence from the geopotential data is used, the resulting NH "warm" minus "undisturbed" phase composite has no extratropical grid point that is significantly different from zero.

In summary, the present work finds no credible evidence for a significant SO influence on the zonal mean flow in the extratropical NH stratosphere, while adding some limited evidence to support vLL's picture of the warm SO phase influence on the winter mean NH standing wave pattern. Unfortunately, even with the increased data record now available, the statistical significance of this result is still not clearly established. A major problem in this regard is the difficulty in separating QBO and SO influences with only a 34-year record.

In a somewhat similar study Baldwin and O'Sullivan (1993) have examined the connection between the DJF mean extratropical tropospheric and stratospheric stationary wave pattern. Since the extratropical tropospheric circulation is well correlated with the SO, their work sheds light on possible SO effects in the stratosphere. Baldwin and O'Sullivan's conclusions appear to be broadly consistent with those of the present study. In particular they find the clearest SO effects to be on the amplitude of stratospheric stationary waves. Baldwin and O'Sullivan also conclude that QBO influence on the zonal-mean polar vortex appears to be much stronger than that associated with the SO.

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