JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D23, PAGES 31,787–31,794, DECEMBER 16, 2001

Relation of size and displacement of the 300 mbar north circumpolar vortex to QBO, El Nino, and sunspot number, 1963–2000

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Abstract. The size of the 300 mbar north circumpolar vortex, and its eastern, western, date line, and Greenwich hemisphere components, is estimated for the period 1963–2000 by planimetering the area poleward of 300 mbar contours in the main belt of westerlies on the mean-monthly polar stereographic analyses of the Institute of Meteorology of the Free University of Berlin. On the basis of the superposed epoch method, there is little evidence of a relation between vortex size and phase of the QBO, but significant at the 90% level or better is the tendency for the vortex to be less displaced into the eastern hemisphere in the east-wind phase of the QBO, for the vortex to be expanded near the time of Nino 3 sea surface temperature maximum (El Nino) but contracted 3–4 seasons after, and for the vortex to be displaced farther into the date line hemisphere when there is an El Nino. There is also an impressive tendency for the winter vortex to be less displaced into the eastern hemisphere at the time of El Nino. The tendency for the vortex to be contracted near sunspot maximum, and expanded near sunspot minimum, is significant at only about the 80% level because of the small sample size.

1. Introduction

There have been a number of studies of the variation in size and displacement of the north circumpolar vortex at or near jet stream level [e.g., *Angell and Korshover*, 1977; *Markham*, 1985; *Angell*, 1992; *Burnett*, 1993; *Davis and Benkovic*, 1992, 1994; *Waugh*, 1997; *Angell*, 1998; *Frauenfeld and Davis*, 2000]. With the recent surge of interest in the North Atlantic Oscillation (NAO) [*Hurrell*, 1995; *Rogers and Mosley-Thompson*, 1995; *Rogers*, 1997; *Hurrell and van Loon*, 1997; *Otterman et al*., 1999; *Wallace*, 2000; *Dickson et al*., 2000] and Arctic Oscillation (AO) [*Thompson and Wallace*, 1998; *Baldwin and Dunkerton*, 1999], these vortex analyses become of greater interest because NAO, AO, and vortex size and displacement should be related, and all are important in the monitoring of climate change. An attractive feature of the vortex from a climatic point of view is its integrative aspect, whereby all wave numbers contribute both by phase and amplitude to its size and displacement.

The close relation between NAO and AO is already well known [e.g., *Kerr*, 1999; *Wallace*, 2000]. It is planned to examine the relation between NAO and AO, and vortex size and displacement in detail, and preliminary thereto, the relation between NAO and vortex size is considered briefly in section 3. As a backdrop for these detailed studies, this paper compares the variation in size and displacement of the 300 mbar north circumpolar vortex with the QBO as defined by the 50 mbar zonal wind at Singapore (1°N); El Nino as defined by the sea surface temperature (SST) in the Nino3 region (5°S–5°N, 90°–150°W) of eastern equatorial Pacific; and 11-year solar cycle as defined by sunspot number. Knowledge of these relations is useful in the study of climate and climate change in general, as well as understanding the association between vortex size and displacement, and NAO and AO.

2. Procedures

The mean-monthly analyses of the Institute of Meteorology of the Free University of Berlin [e.g., *Labitzke et al*., 1986] are on Northern Hemisphere polar stereographic maps, or map projections centered on the North Pole. These meticulous analyses at 700, 300, 100, 50, and 30 mbar begin in January 1963 and continue through 2000. The analyses are hand produced using such tools as thermal wind to ensure continuity between pressure surfaces. The only significant change in analysis procedure during the 38 years is the recent consideration of satellite temperature data over the oceans. Despite this change in procedures, the impact of which is difficult to judge, the author believes that the Berlin analyses are the best available for the purposes of this paper. As in previous work [*Angell*, 1992, 1998], the 300 mbar pressure surface is used in this analysis because the tropospheric north circumpolar vortex is well defined at this jet stream level. The 300 mbar geopotential contours chosen to delimit the vortex are the 9120 m contour in winter (DJF), the 9280 m contour in spring (MAM) and autumn (SON), and the 9440 m contour in summer (JJA), all in the core of the midlatitude westerlies, or at about 40°N in DJF and MAM, 45°N in SON, and 50°N in JJA.

The size of the 300 mbar north circumpolar vortex, and its eastern hemisphere component, western hemisphere component, date line hemisphere component (component centered on the date line or 180th meridian), and Greenwich hemisphere component (component centered on the Greenwich or prime meridian), is estimated from the Berlin 300 mbar polar stereographic maps by means of a planimeter, which on these maps can measure vortex size to about the nearest 0.5% and hemisphere size to about the nearest 1%. As an example, Figure 1 shows at the top a polar stereographic map projection

Paper number 2001JD000473.

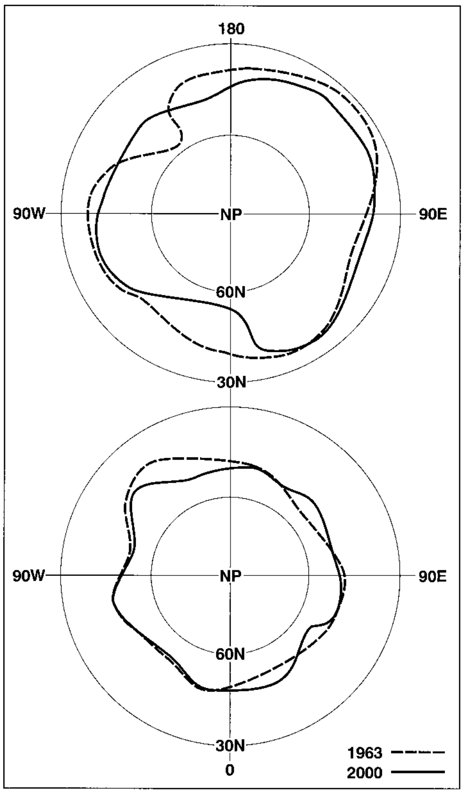

Figure 1. Polar stereographic 300 mbar maps showing (top) the trace of the 9120 m height contour in January 1963 (dashed line) and January 2000 (solid line), and (bottom) the trace of the 9440 height contour in July 1963 (dashed line) and July 2000 (solid line). Vortex size is estimated from the planimetered area poleward of these contours in the main belt of westerlies, vortex displacement, or eccentricity from the percentage difference in size of eastern and western hemisphere components of the vortex and date line and Greenwich hemisphere components of the vortex.

centered on the North Pole (NP), with traces of the 9120 m height contour for January 1963 (dashed line) and January 2000 (solid line) superimposed. The solid line usually falls within the dashed line, and planimetering of the area within the dashed and solid lines indicates a 10% decrease in vortex size between January 1963 and January 2000. The 10% contraction of the vortex is associated with a 76 m increase in height of the 300 mbar surface around the hemisphere at 40°N. Thus the change in 300 mbar vortex size reflects a change in height of the 300 mbar surface in the latitude band of the reference contour. At the bottom of Figure 1 is a polar stereographic map with traces of the 9440 m height contour for July 1963 (dashed line) and July 2000 (solid line). In this case the difference in vortex size between the first and the last year of record is not obvious, though planimetering shows that the vortex size in July 2000 is 3% less than in July 1963.

The displacement of the vortex from the North Pole (vortex eccentricity), and the change in this displacement with time, is estimated by comparison of the size of the eastern hemisphere component of the vortex to the size of the western hemisphere component, and the size of the date line hemisphere component of the vortex to the size of the Greenwich hemisphere component. Thus in January 1963 the size of the eastern hemisphere component of the vortex is 24% greater than the size of the western hemisphere component, signifying a vortex displaced into the eastern hemisphere, but in January 2000, the size of the eastern hemisphere component is 45% greater than the western hemisphere component, signifying displacement of the vortex farther into the eastern hemisphere (see Figure 1, top). To a first approximation the displacement of the vortex center from the North Pole in degrees latitude is half the percentage difference in hemisphere size, or 12° and 22° of latitude, respectively, along the 90°E meridian in January 1963 and January 2000. However, because of the approximate nature of the above relationship, in the remainder of the paper only the percentage differences in hemisphere size are given. In January 1963 the size of the date line hemisphere component of the vortex is only 6% greater than the Greenwich hemisphere component, and this difference in size increases to only 11% in January 2000, indicating little displacement, or change in displacement, along the 180th meridian. In July the vortex is basically centered on the North Pole in both 1963 and 2000 (see Figure 1, bottom), so in this month there is little displacement of the vortex from the North Pole, or change in this displacement.

In the following, the monthly vortex-size and hemisphere-size values are averaged to provide seasonal and annual sizes, which are then transformed into anomalies by finding the deviations from 1963 to 2000 means.

3. Background

Figure 2 (top) shows the variation in annual 300 mbar vortex-size anomaly (in percent) for the period 1963–2000. As would be inferred from Figure 1, the vortex has contracted over the period of record but not uniformly with time. On the basis of least squares linear regression, and 2 standard errors of estimate thereof, the 38-year trend in vortex size is −1.4 ± 0.6%/decade, but with the greatest vortex contraction in 1989,

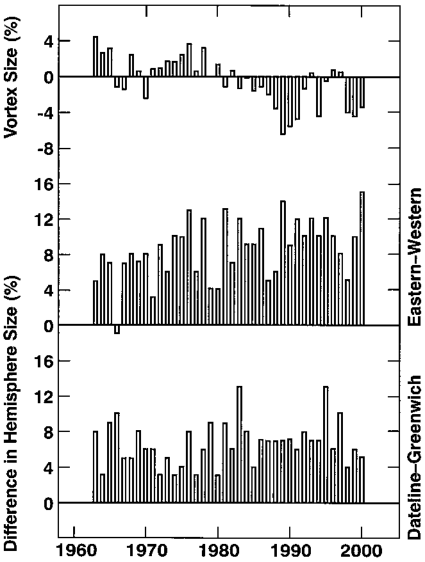

Figure 2. (top) Variation in annual size anomaly (%) of the 300 mbar north circumpolar vortex, and the annual percentage by which the size of the eastern hemisphere component of the vortex exceeds the size of the western hemisphere component (middle), and (bottom) the size of the date line hemisphere component exceeds the size of the Greenwich Hemisphere component.

a year of sunspot maximum. This vortex contraction is significant at the 95% level in all seasons, though barely so in spring. The middle trace of Figure 2 shows the percentage by which the annual size of the eastern hemisphere component of the vortex exceeds the size of the western hemisphere component. The minimum value is in 1966 (western hemisphere component larger than eastern hemisphere component), and the maximum value of 15% is in 2000. The trend for the 38 years is 1.2 ± 0.8%/decade, with the trend greatest in winter and least in summer. Shown at the bottom of Figure 2 is the percentage by which the annual size of the date line hemisphere component of the vortex exceeds the size of the Greenwich hemisphere component. The trend is only 0.2 ± 0.7%/decade, but with the unexpected finding of a significant positive trend in winter (vortex becoming displaced more into the date line hemisphere in this season) counterbalanced by negative trends in summer and autumn.

In the average for the 38 years, the percentage by which the size of the eastern hemisphere component of the vortex exceeds the size of the western hemisphere component is 20% in winter, 2% in spring, 1% in summer, 10% in autumn, and 8% for the year as a whole. The average percentage by which the size of the date line hemisphere component of the vortex exceeds the size of the Greenwich hemisphere component is 9% in winter, 3% in spring and summer, 11% in autumn, and 6% for the year as a whole.

In the context of other work, it is of interest to see if a contracted 300 mbar vortex is associated with a deep vortex (vortex with below-average height of the 300 mbar surface at or near the North Pole, or vice versa). Figure 3 shows that on the basis of the Berlin maps, the decrease in 300 mbar vortex size during 1963–2000 (middle trace) is not accompanied by a long-term change in height of the 300 mbar surface at the North Pole (top trace). The correlation between annual values is small but positive; that is, there is a tendency for a contracted vortex to be a deep vortex. This tendency is apparent in all seasons but is greatest in winter and spring. Essentially the same results are obtained if the average 300 mbar height north of 80°N based on the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] is used. On the basis of map composites, *Holton and Tan* [1980] found a strong tendency at 50 mbar for a contracted vortex (as defined by the latitude of maximum zonal wind) to be a deep vortex. This tendency is not nearly so obvious at 300 mbar.

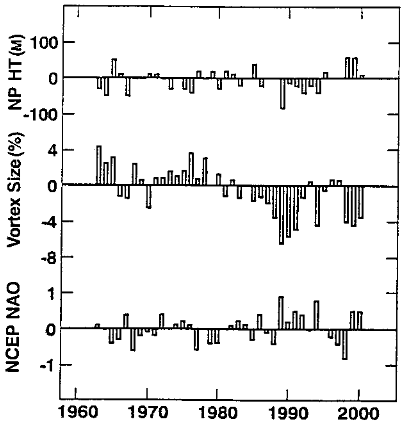

Figure 3. Based on the Berlin maps, comparison of the variation in annual size anomaly (%) of the 300 mb north circumpolar vortex (middle), and annual height anomaly (meters) of the 300 mb surface at the North Pole (top). (bottom) Annual variation in the National Centers for Environmental Prediction (NCEP) index of the North Atlantic Oscillation (NAO).

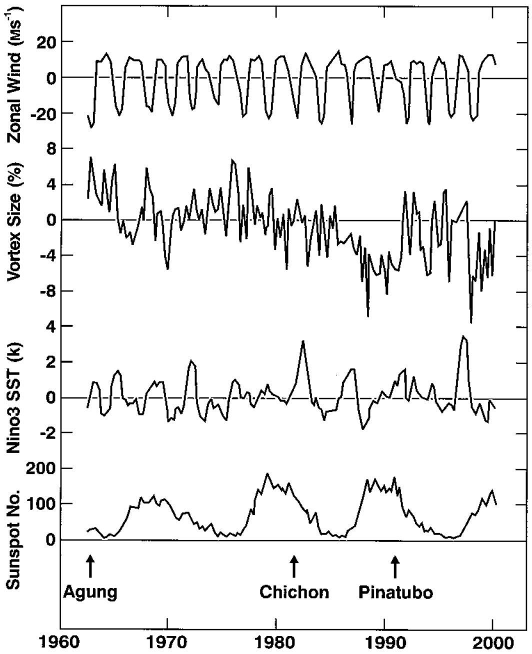

Figure 4. From top to bottom the variation in seasonal values of Singapore 50 mb zonal wind (m s^{-1}), size anomaly of the 300 mb north circumpolar vortex (%), Nino 3 SST anomaly (K), and sunspot number. Abscissa tick marks are in summer.

The bottom trace of Figure 3 shows the variation in the National Centers for Environmental Prediction (NCEP) index of the NAO, as reported in the NCEP Climate Diagnostics Bulletin. The long-term decrease in 300 mb vortex size is accompanied by a less obvious long-term increase in NAO, and the annual anomalies of vortex size and NAO are often of opposite sense, yielding a significant correlation of −0.35. The correlation between the two is a highly significant −0.58 in winter and a significant −0.36 in spring but is nearly zero in summer and autumn. At least in winter there is an impressive tendency for a contracted vortex to be associated with a positive value of the NAO. Because the AO is circumpolar, one might expect an even better relation between AO and vortex size. As mentioned in section 1, it is planned to examine in detail the relation between size, displacement and depth of the 300 mb north circumpolar vortex, and NAO and AO.

4. Superposed Epoch Method

Figure 4 compares the seasonal variation in the size of the 300 mb north circumpolar vortex with the quasi-biennial oscillation (QBO) as defined by the 50 mb zonal wind at Singapore (1°N); El Nino as defined by the sea surface temperature (SST) in the Nino3 region (5°S–5°N, 90°–150°W) of eastern equatorial Pacific; and 11-year solar cycle as defined by sunspot number. Because of the variability in seasonal vortex size it is difficult to define relations visually, except perhaps in the case of sunspot number. In this paper the relations of vortex size and displacement to QBO, El Nino, and sunspot number are

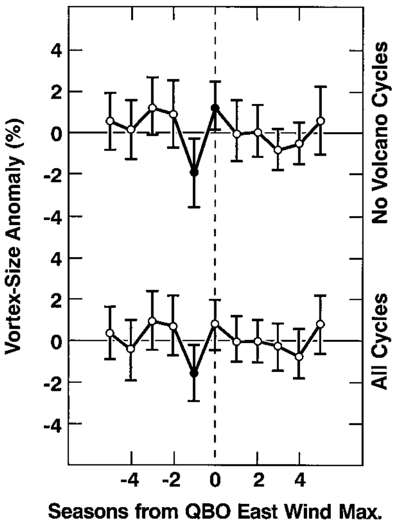

Figure 5. Average vortex-size anomaly (%) as a function of number of seasons before (negative abscissa) and after the season of Singapore 50 mb east-wind maximum, based on application of the superposed epoch method to the 13 QBO cycles without major volcanic eruptions (top) and the 16 cycles, which include Agung, El Chichon, and Pinatubo eruptions (bottom). Vertical bars extend 2 standard errors of the mean both sides of the average vortex-size anomalies (as determined from the anomalies in each of the cycles) but represent only 90% confidence intervals because of the sampling error in the standard deviation when there is a relatively small sample size.

estimated by use of the superposed epoch method [*Panofsky and Brier*, 1958]. Thus in the case of the QBO, seasonal vortex-size anomalies in percent, and differences in hemisphere size in percent, are centered on the season of 50 mb east-wind maximum at Singapore (better defined than the west-wind maximum, as shown in Figure 4), and their average value in this season, and the five seasons, both sides thereof, determined. In the case of El Nino, the vortex-size anomalies, and the differences in hemisphere size, are centered on the season of Nino3 (5°S–5°N, 150°–90°W) SST maximum, and the average value in this season, and the five seasons, both sides thereof, determined. The use of only five seasons has been criticized on the basis of the possible interest in the effect of El Nino on vortex size and displacement over several years. However, it was found that the use of a 21-season interval rather than an 11-season interval (because the recurrence interval of Nino3 SST is about twice that of QBO) resulted in erratic vortex sizes at the extremities of the interval, masking the variation in vortex size near SST maximum as well as increasing the size of the confidence intervals there. This, in combination with the simplicity introduced by having QBO, El Nino, and sunspot number in the same format on the diagrams, resulted in the decision to present the relation between vortex and Nino3 SST for only 11 seasons. In the case of sunspot number, the annual vortex-size anomalies are centered on the year of sunspot maximum, and the average vortex size in this year, and 5 years both sides thereof determined. The advantage of defining the relations by the superposed epoch method rather than by lagged correlations [*Angell*, 1992; *Frauenfeld and Davis*, 2000] is that thereby the strength of the relation is expressed in terms of the dimension of the variable under study rather than by a dimensionless correlation coefficient.

It seemed important to consider the possible impact of Agung, El Chichon, and Pinatubo eruptions on the relation between vortex size, and QBO, El Nino, and sunspot number, because of the finding of *Robock and Mao* [1992, 1995] of a contracted vortex in the winter season following these major eruptions. Accordingly, the superposed epoch method has been applied twice, once with the 13 QBO cycles and 7 El Nino episodes, which do not include these eruptions, and once for all 16 QBO cycles and 10 El Nino episodes. In the case of sunspot number the superposed epoch analysis is again done twice, once without vortex-size data in the year of, and the year following, each eruption, and once with all years of data.

The significance of average vortex-size anomalies, and average differences in hemisphere size, is estimated for each of the 11 seasons or years (five seasons or years both sides of the centered season) from 2 standard errors of the mean of the anomaly and difference values for each of the QBO cycles, El Nino episodes, and 11-year sunspot cycles. To minimize the impact of trend on the significance estimates, deviations from the mean are determined for the 11 values in each of the cycles or episodes. The 2 standard error values thus determined are plotted in the figures as vertical bars extending both sides of average values. Because of the sampling error in the standard deviation when there is a relatively small sample size, the lengths of these vertical bars only represent 90% confidence intervals in the case of QBO, barely 90% confidence intervals in the case of El Nino, and barely 80% confidence intervals in the case of sunspot number.

An obvious concern in the use of the superposed epoch method in this manner is the degree to which the relation between QBO, and vortex size and displacement, is contaminated by the relation between El Nino, and vortex size and displacement, and vice versa. Owing to the difference between the QBO period of about 27 months and the irregular El Nino period of about 5 years, there is little lag correlation between 50 mb zonal wind at Singapore and Nino3 SST, the lag correlations up to five seasons not exceeding 0.12. These small correlations suggest that there should be little contamination of the relation between vortex and QBO by the relation between vortex and El Nino. As a further check on the independence of QBO and El Nino in this regard, the variation of Nino3 SST anomaly from five seasons before to five seasons after the QBO east-wind maximum was evaluated. The average SST values vary gradually from 0.3 K above average two seasons before east-wind maximum to 0.2 K below average five seasons after east-wind maximum. These values fall well within 2 standard errors of the mean, so there is no evidence from the superposed epoch method either that the relation between vortex and QBO is being appreciably contaminated by the relation between vortex and El Nino, and vice versa. Nevertheless, certainly an advantage of the lag correlation method of defining the relations between vortex, and QBO and El Nino, is that the two relations can be disentangled by the use of partial correlation coefficients.

5. Vortex-QBO Relations

Figure 5 presents the average size anomaly (%) of the 300 mb north circumpolar vortex from five seasons before (negative abscissa) to five seasons after the season of 50 mb east-wind maximum at Singapore. The trace at the top shows the relation on the basis of the 13 QBO cycles not affected by Agung, El Chichon, or Pinatubo eruptions, and the trace at the bottom shows the relation based on all 16 cycles. It is seen that

Table 1. Percentage Difference in Seasonal Vortex Size When Singapore 50 mb Zonal Wind is From the East Compared to From the West, and the Difference in the Percentage by Which the Size of the Eastern Hemisphere Component of the Vortex Exceeds the Size of the Western Hemisphere Component (EH-WH), and the Size of the Date Line Hemisphere Component Exceeds the Size of the Greenwich Hemisphere Component (DH-GH), When the QBO Is in the East-Wind Phase Compared to the West-Wind Phase[a]

	Winter	Spring	Summer	Autumn
Vortex size	0.4 ± 1.9	−0.2 ± 1.6	−0.1 ± 2.2	−0.9 ± 1.7
EH-WH	−4.2 ± 3.6	−1.5 ± 2.8	−1.4 ± 2.7	−2.4 ± 3.4
DH-GH	−1.0 ± 3.2	1.0 ± 2.4	−0.7 ± 3.4	0 ± 2.6

[a] Addenda are twice the square root of the sum of the squares of the standard deviations of seasonal vortex size, and difference in hemisphere size, for each of the two phases divided by the number of seasons in each phase (usually 19).

the impact of the volcanoes on the results is small. There is no convincing evidence of a relation between the vortex size and the phase of the QBO, the only 90% confidence intervals not intersecting the zero axis, indicating an expanded vortex in the season of QBO east-wind maximum but a contracted vortex only one season earlier. The proximity of these two values of opposite sense does not provide confidence in their representativeness. Furthermore, the top line of Table 1 shows only a negligible difference in seasonal vortex size in east- and west-wind phases of the QBO. *Holton and Tan* [1980] found a strong tendency in winter for a deeper vortex in the west-wind phase of the QBO than in the east-wind phase, as well as a more contracted vortex then as defined by the latitude of maximum zonal wind. While the positive winter correlation in Table 1 does signify a contracted vortex in the west-wind phase of the QBO, the tendency is so small that basically, the Holton and Tan findings at 50 mb are not being replicated by the Berlin maps at 300 mb.

Figure 6 shows the percentage difference in the size of the eastern and western hemisphere components of the vortex relative to the season of the QBO east-wind maximum, based on the 13 QBO cycles not affected by Agung, El Chichon, or Pinatubo eruptions. There is a fairly consistent change in the percentage by which the size of the eastern hemisphere component of the vortex exceeds the size of the western hemisphere component from about 5% near QBO east-wind maximum (significantly different from the average difference of 8% at the 90% level) to about 10% five seasons before and after the east-wind maximum, or near the west-wind maximum. The middle line of Table 1 shows that the tendency for less displacement of the 300 mb vortex into the eastern hemisphere in the east-wind phase of the QBO is apparent in all seasons but is greatest and most significant in winter. It is not obvious why the vortex displacement should be related to the QBO, especially since the magnitude of the QBO varies little with longitude, but the evidence is quite impressive that it is.

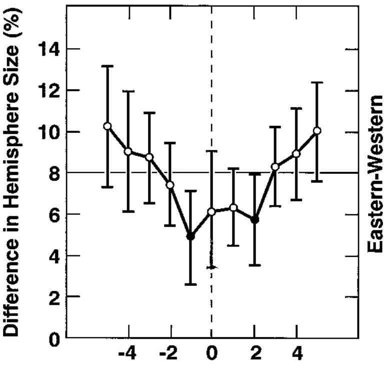

Figure 6. Percentage by which the size of the eastern hemisphere component of the vortex exceeds the size of the western hemisphere component, as a function of number of seasons before and after the 13 seasons of QBO east-wind maximum. Vertical bars are 90% confidence intervals (see Figure 5 caption).

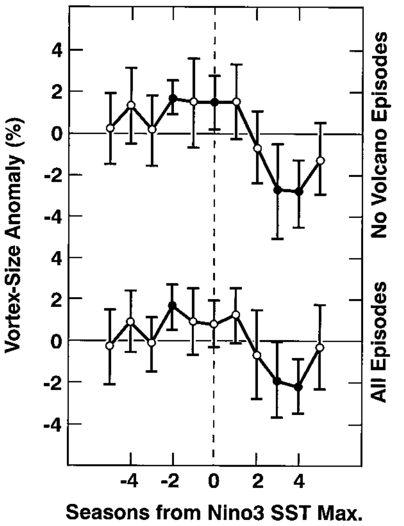

Figure 7. Average vortex-size anomaly (%) as a function of number of seasons before and after the season of Nino3 SST maximum, based on application of the superposed epoch method to the seven El Nino episodes without major volcanic eruptions (top) and the 10 episodes, which include Agung, El Chichon, and Pinatubo eruptions (bottom). Vertical bars extend 2 standard errors of the mean both sides of the average vortex-size anomalies but barely represent 90% confidence intervals because of the sampling error in such a small sample size.

There is no consistent difference in the size of the date line and Greenwich hemisphere components of the vortex relative to the season of the QBO east-wind maximum, and the bottom line of Table 1 shows that there is also no consistency in the seasonal values of this difference. Accordingly, a diagram of this relation is not shown.

6. Vortex-El Nino Relations

Figure 7 presents the average size anomaly (%) of the 300 mb north circumpolar vortex from five seasons before to five seasons after the season of Nino3 SST maximum. The trace at the top of Figure 7 shows the relation, based on the seven El Nino episodes, not affected by Agung, El Chichon, or Pinatubo eruptions (1965, 1969, 1972, 1976, 1979, 1987, and 1997), the trace at the bottom of the relation, based on all 10 El Nino episodes, including those of 1963, 1983, and 1992. In both cases there is a 1–2% expansion of the vortex near the time of Nino3

Table 2. Percentage Difference in Seasonal Vortex Size When Nino3 SST Is Above Average Compared to Below Average (El Nino Episode Minus La Nina Episode), and the Difference in the Percentage by Which the Size of the Eastern Hemisphere Component of the Vortex Exceeds the Size of the Western Hemisphere Component, and the Size of the Date Line Hemisphere Component Exceeds the Size of the Greenwich Hemisphere Component, When There Is an El Nino Episode Compared to a La Nina Episode[a]

	Winter	Spring	Summer	Autumn
Vortex size	1.7 ± 1.8	0.5 ± 1.8	2.7 ± 2.1	0.1 ± 1.8
EH-WH	−6.8 ± 3.9	−0.5 ± 2.7	1.0 ± 2.8	−1.6 ± 3.4
DH-GH	0.6 ± 3.0	0.7 ± 2.6	4.7 ± 3.2	−0.5 ± 2.8

[a] Otherwise see Table 1 caption.

SST maximum (significant at the 90% level), and a 2–3% contraction of the vortex 3–4 seasons after SST maximum (significant at the 95% level). The top line of Table 2 shows that the difference in vortex size when Nino3 SST is above average compared to below average is largest and most significant in summer, followed by winter.

Frauenfeld and Davis [2000] find no significant correlation at any time lag between 500 mb circumpolar vortex area and Southern Oscillation Index (SOI) or Nino3.4 SST, whereas this analysis finds the relation between vortex size and Nino3 SST significant at close to the 95% level. Their analysis was carried out using different maps for a different time period (1946–1994) for a different level (500 mb), as well as using a different procedure (vortex area estimated from the distance between given jet stream contours and the North Pole at 5° longitude intervals). A reviewer suggested that the epoch analysis may be highlighting relationships not easily seen through standard correlations.

Figure 8 shows the percentage difference in the size of the date line and Greenwich hemisphere components of the vortex relative to the season of Nino3 SST maximum, based on the seven El Nino episodes not affected by Agung, El Chichon, or Pinatubo eruptions. There is a fairly consistent change in the percentage by which the size of the date line hemisphere component of the vortex exceeds the size of the Greenwich hemisphere component, from nearly 9% one season before Nino3 SST maximum to only about 3% three seasons after this maximum. Both values are significantly different (at the 90% level) from the average 6% difference in the sizes of these hemisphere components of the vortex. This agrees with the finding of *Frauenfeld and Davis* [2000, Figure 1] of an expanded 500 mb circumpolar vortex over the central Pacific during warm El Nino-Southern Oscillation (ENSO) periods. The bottom line of Table 2 shows that this tendency for greater displacement of the 300 mb vortex into the date line hemisphere when Nino3 SST is above average is apparent in winter, spring, and summer but is by far the largest and most significant in summer.

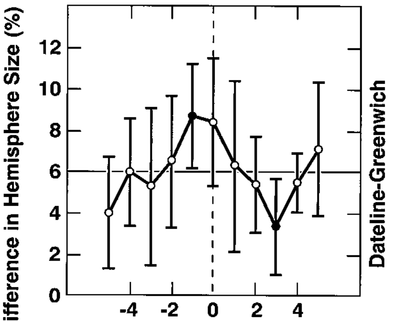

Figure 8. Percentage by which the size of the date line hemisphere component of the vortex exceeds the size of the Greenwich hemisphere component as a function of number of seasons before and after the seven seasons of Nino3 SST maximum. Vertical bars are barely 90% confidence intervals (see Figure 7 caption).

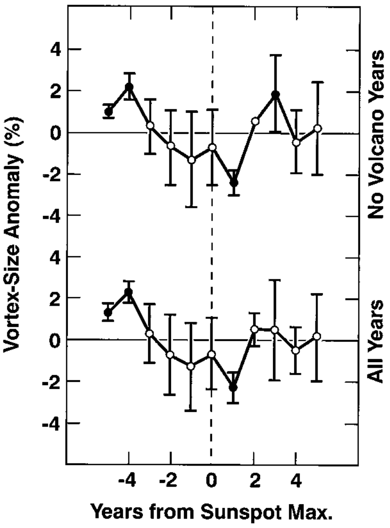

Figure 9. Average vortex-size anomaly (%) as a function of number of years before and after the year of sunspot maximum, based on application of the superposed epoch method to 3½ solar cycles and excluding anomalies in the year of, and year following, Agung, El Chichon, and Pinatubo eruptions (top) but including the anomalies in all years (bottom). Vertical bars extend 2 standard errors of the mean both sides of the average vortex size anomalies but barely represent 80% confidence intervals because of the sampling error in such a very small sample size.

There is no consistent difference in the size of eastern and western hemisphere components of the vortex relative to the season of Nino3 SST maximum, but the middle line of Table 2 shows an impressive tendency in winter for less displacement of the vortex into the eastern hemisphere when Nino3 SST is above average. This tendency is masked in a diagram such as Figure 8 by the opposite tendency in summer.

7. Vortex-Sunspot Number Relations

Figure 4 showed the relation between the vortex size and the sunspot number. The evidence for a contracted vortex near sunspot maximum is tantalizing but not completely convincing. The evidence is best for the sunspot maximum around 1990 and worst for the sunspot maximum around 1980. On the basis of application of the superposed epoch method to the 3⅓ solar cycles available, there is a 1–2% contraction of the vortex near sunspot maximum (Figure 9) but with the relation quite erratic. If annual vortex size is centered on the year of sunspot minimum the relation is more impressive than shown in Figure 9, the vortex size 2% above average in the year of sunspot minimum, and the vertical bars (2 standard errors of the mean)

Table 3. Percentage Difference in Seasonal Vortex Size When the Sunspot Number Is Above Average Compared to Below Average, and the Difference in the Percentage by Which the Size of the Eastern Hemisphere Component of the Vortex Exceeds the Size of the Western Hemisphere Component, and the Size of the Date Line Hemisphere Component Exceeds the Size of the Greenwich Hemisphere Component, When Sunspot Number Is Above Average Compared to Below Average[a]

	Winter	Spring	Summer	Autumn
Vortex size	−2.6 ± 1.5	−1.3 ± 1.7	−3.4 ± 1.9	−0.9 ± 1.6
EH-WH	3.4 ± 4.4	0 ± 2.6	0.6 ± 2.8	−0.8 ± 3.4
DH-GH	−1.2 ± 2.1	0 ± 2.3	1.4 ± 3.5	0.6 ± 2.6

[a] Otherwise see Table 1 caption.

not intersecting the zero axis in that year or the year preceding. Since the vertical bars are only 80% confidence intervals because of the small sample size, the evidence for vortex contraction near sunspot maximum, and vortex expansion near sunspot minimum, is estimated to be significant at about the 80% level.

The top line of Table 3 shows the relation between vortex size and sunspot number by season. The tendency for a contracted vortex near sunspot maximum is apparent in all seasons but is strongest and most significant in summer, followed by winter. The former is in agreement with the finding of *van Loon and Shea* [2000] that during July and August, Northern Hemisphere heights and temperatures from midtroposphere to midstratosphere are greater at sunspot maximum than at sunspot minimum. The bottom two lines of Table 3 show that the only evidence of a relation between sunspot number and vortex eccentricity is a tendency for the winter vortex to be displaced farther into the eastern hemisphere when the sunspot number is above average.

8. Summary and Discussion

Following are the main findings with regard to the relation between size and displacement of the 300 mb north circumpolar vortex, and QBO, El Nino, and sunspot number, for the period 1963–2000.

1. There is little evidence of a relation between vortex size and phase of the 50 mb QBO.
2. The vortex is less displaced into the eastern hemisphere near the time of QBO east-wind maximum (significance level 90%). The difference in displacement for east-wind and west-wind phases of the QBO is observed in all seasons but is largest and most significant in winter.
3. The vortex is expanded near the time of Nino3 SST maximum (significance level 90%). The difference in vortex size when Nino3 SST is above average (El Nino episode) compared to below average (La Nina episode) is observed in all seasons but is largest and most significant in summer, followed by winter.
4. The vortex is contracted three–four seasons after Nino3 SST maximum (significance level 95%).
5. The vortex is displaced farther into the date line hemisphere during El Nino (significance level 90%). This difference in displacement for El Nino and La Nina episodes is observed in all seasons but autumn, but is largest and most significant in summer.
6. There is an impressive tendency for the winter vortex to be less displaced into the eastern hemisphere during El Nino.
7. The vortex is contracted near sunspot maximum, and expanded near sunspot minimum, at about the 80% significance level. The difference in vortex size when sunspot number is above average compared to below average is observed in all seasons but is largest and most significant in summer.
8. There is little evidence of a relation between sunspot number and vortex eccentricity except for a tendency for the winter vortex to be displaced farther into the eastern hemisphere when sunspot number is above average.

The question arises as to the extent to which the variation in vortex size and displacement can be related to changes in surface temperature and to precipitation. For example, does the tendency for the vortex to be less displaced into the eastern hemisphere in the east-wind phase of the QBO mean that in the western hemisphere there is a cooling and an increase in precipitation at that time? Are the variations additive? That is, if the east-wind phase of the QBO occurs at the time of an El Nino, is the tendency for cooler and wetter weather in the western hemisphere enhanced? If both occur near the time of sunspot minimum, is the tendency enhanced even more? If the relations turn out to be additive, and this is not easy to demonstrate with the data record at hand, the present study is more than an academic exercise since it facilitates association of the most basic features of the atmospheric circulation to weather and climate.

9. Conclusion

El Nino has a significant impact on both size and displacement of the 300 mb north circumpolar vortex. The QBO has a significant impact on vortex displacement. There is evidence of a relation between vortex size and 11-year solar cycle as measured by sunspot number. Accordingly, size and displacement of this vortex should represent a useful complement, and supplement, to both North Atlantic Oscillation (NAO) and Arctic Oscillation (AO).

Acknowledgments. Karin Labitzke and the staff of the Institute of Meteorology of the Free University of Berlin have been most generous in providing me for more than two decades with the polar stereographic maps used in this analysis. Julian Wang of the Air Resources Laboratory, NOAA, provided me with pertinent NCEP/NCAR reanalysis data, and pointed out the similarity in the results on vortex size and displacement obtained from the Berlin maps and from reanalysis. I thank Dian Seidel and Becky Ross of the Air Resources Laboratory of NOAA, Craig Long of the Climate Prediction Center of NOAA, and three anonymous referees for their unusually thorough and useful comments on the manuscript.

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(Received February 7, 2001; revised June 29, 2001;
accepted September 6, 2001.)