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Matt Jackson
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**TEMPORAL VARIATIONS
IN THE NORTHERN HEMISPHERE
CIRCUMPOLAR VORTEX**

**A Thesis
Presented to
The Faculty of the Department of Meteorology
San Jose State University**

**In Partial Fulfillment
of the Requirements for the Degree
Master of Science**

**By
Matt Jackson
May, 1995**

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ABSTRACT

TEMPORAL VARIATIONS IN THE NORTHERN HEMISPHERE CIRCUMPOLAR VORTEX

by Matt Jackson

Daily and monthly averaged Northern Hemisphere geopotential height data was examined to calculate time series of circumpolar vortex eccentricity and position, as well as the amplitude of wave one. Time series were examined to determine long term trends and variations by graphical, statistical, and spectral analyses. The relationships between these parameters and other phenomena, including sunspot numbers and quasi-biennial variations in the equatorial 30 mb zonal wind were also examined

Vortex eccentricity exhibits high and low frequency variations. The primary short term variation is an annual cycle in which larger values occur during winter and smaller values during summer. Vortex eccentricity was positively correlated with wave one amplitudes at the 99% confidence level. Monthly vortex eccentricity values separated according to QBO west phase during sunspot minima and QBO east phase during sunspot maxima were determined to vary from each other at the 95% significance level as determined by the Student's T test.

ACKNOWLEDGEMENTS

Primary credit for this thesis must go to Ms. Loree Glenn for giving me the relatively insane idea of returning to school to pursue a Master's in the first place. I owe a great deal to all the meteorology students who assisted me with homework, reminded me of the proper method for differentiating equations and, coincidentally, shared quite a few beers. Special thanks go to Dan Tyler, Joel O'Camb, Dolcie Drake, Steve Bellavance, and Fernando Aluzzi.

Doctor Alison F. C. Bridger is effusively acknowledged for her role as my primary Thesis Advisor, thereby providing me with both a research topic and employment. Professors Doug Sinton and Jerry Steffens served on my thesis committee and had the dubious honor of reading preliminary drafts and making valuable suggestions for improvement. Doctor Peter Lester is hereby acknowledged for reminding his students that Meteorology is supposed to be fun and challenging.

Thanks of a "close and personal nature" go to Kim Spomer for providing psychological counseling during the last year and a half, as well as for giving me a reason to finish this thing off and get an actual life. Finally, this thesis is dedicated to my niece, Ms. Cara Lee Snellen, in the hope that her college education will take less time to complete than mine did.

TABLE OF CONTENTS

	Page
ABSTRACT	iv
ACKNOWLEDGEMENTS	v
CHAPTER	
1. INTRODUCTION	1
1.1 The Circumpolar Vortex	1
1.2 Previous Studies	4
1.3 Goals of the Current Investigation	11
2. METHODS AND ANALYSES	12
2.1 Data Source	12
2.2 Calculation of Vortex Parameters	13
2.2.a METHOD 1: Mid-Latitudinal Average	14
2.2.b METHOD 2: Maximum Height Gradient	18
2.2.c La Seur Method Using Wave Number One Height Field	22
2.3 Analysis Methods	27
2.4 Verification	29
3. RESULTS OF DAILY ANALYSES	46
3.1 Overview	46
3.2 Time Series	49
3.2.a 500 Mb Eccentricity and Amplitude	49
3.2.b 200 Mb Eccentricity and Amplitude	51
3.2.c 500 Mb Vortex Locations	54
3.2.d 200 Mb Vortex Locations	57
3.3 Statistical Analyses	57
3.3.a 500 Mb Eccentricity and Amplitude	57
3.3.b 500 Mb Vortex Locations	66
3.3.c 200 Mb Eccentricity and Amplitude	67
3.3.d 200 Mb Vortex Locations	75
3.3.e 500 Mb Correlations	76
3.3.f 200 Mb Correlations	86
3.3.g Decadal Averages	92
3.4 Spectral Analyses	96
3.4.a 500 Mb Eccentricity and Amplitude	96
3.4.b 200 Mb Eccentricity and Amplitude	99
3.4.c 500 Mb Vortex Location	101
3.4.d 200 Mb Vortex Location	104
3.5 Summary	104

CHAPTER	Page
4. RESULTS OF MONTHLY ANALYSES	107
4.1 Time Series Of Monthly Eccentricity	108
4.2 Statistics From Mean Monthly Data	111
4.2.a 500 Mb Data	111
4.1.b 200 Mb Data	115
4.3 Spectral Analyses Of Monthly Eccentricity . .	121
4.4 Summary	123
5. THE POLAR VORTEX AND CLIMATIC VARIATIONS	127
5.1 Experimental Procedures	128
5.1.a Low Frequency Analyses Procedures . .	128
5.1.b Procedures for Separation of Data . .	129
5.1.c Volcanic Eruption Procedures	130
5.2 Low Frequency Analyses	132
5.3 Separation By Sunspot and QBO Phase	138
5.3.a Sunspot Maxima versus Minima	138
5.3.b QBO West versus East	143
5.3.c QBO West versus East During Sunspot Maxima	148
5.3.d QBO West versus East During Sunspot Minima	153
5.3.e Comparisons of QBO Phases and Sunspot Numbers	158
5.3.f Significance	159
5.4 Volcanic Eruptions and Eccentricity	165
5.5 Summary	168
6. SUMMARY, DISCUSSION, AND CONCLUSIONS	172
BIBLIOGRAPHY	179

LIST OF FIGURES

Figure	Page
1.1 Mean Northern Hemispheric 500 mb contours for the month of January	2
2.1 Illustration of method used to compute polar vortex location via centroid of height contours	17
2.2 Northern Hemisphere 500 mb height contours above 20°N at 12Z, December 29, 1952	19
2.3 500 mb height contours used for determining circumpolar vortex location via the La Seur method	20
2.4 Centroid formed by connecting points of maximum height change along each meridian	23
2.5 Height fields composed of (a) mean and wave number one only; (b) mean and wave number two; (c) mean and wave number three; and (d) mean and wave number four	24
2.6 Time series of vortex eccentricity determined by La Seur method using unfiltered height field; (a) using height field with wave numbers greater than one filtered out	26
2.7 (a) Summary of 500 mb polar vortex locations determined by La Seur	30
2.8 Seasonal 300 mb polar vortex locations as determined by Angell and Korshover	33
2.9 Monthly averaged 200 mb vortex locations as determined by equal area method, 1972	34
2.10 Monthly averaged 200 mb vortex locations as determined by equal area method, 1982-1983	35
2.11 Monthly averaged 200 mb vortex locations as determined by La Seur method, 1972	36
2.12 Monthly averaged 200 mb vortex locations as determined by La Seur method, 1982-1983	37
2.13 Monthly averaged 200 mb vortex locations determined by La Seur method utilizing mean 40° latitudinal height contour	40

Figure	Page
2.14 Same as Figure 2.13, but utilizing mean 45° latitudinal height contour	41
2.15 Same as Figure 2.13, but utilizing mean 50° latitudinal height contour	42
2.16 Same as Figure 2.13, but utilizing height contour used in equal area method	43
3.1 Time series of daily 500 mb circumpolar vortex eccentricity values as determined by method 2 . .	47
3.2 Time series of 500 mb circumpolar vortex eccentricity values that have been smoothed . . .	50
3.3 Time series of 500 mb maximum hemispheric wave one amplitude values that has been smoothed	52
3.4 Two time series of 200 mb circumpolar vortex eccentricity values that have been smoothed . . .	53
3.5 Time series of 200 mb maximum hemispheric wave one amplitude values that has been smoothed	55
3.6 Time series of 500 mb vortex locations that have been smoothed	56
3.7 Time series of 200 mb vortex locations that have been smoothed	58
3.8 Histograms of 500 mb circumpolar vortex eccentricity and position	62
3.9 Histograms of 500 mb circumpolar vortex eccentricity and position determined by method 1 for winter and summer months	63
3.10 Histograms of 500 mb circumpolar vortex eccentricity and position determined by method 2 for winter and summer months	64
3.11 Histograms of 200 mb circumpolar vortex eccentricity and position	72
3.12 Histograms of 200 mb circumpolar vortex eccentricity and position determined by method 1 for winter and summer months	73

Figure	Page
3.13 Histograms of 200 mb circumpolar vortex eccentricity and position determined by method 2 for winter and summer months	74
3.14 Scatter plot of 500 mb circumpolar vortex eccentricity against position as determined by method 1	77
3.15 Same as Figure 3.14 but for method 2	78
3.16 Scatter plot of vortex eccentricity against wave one amplitude	82
3.17 Scatter plot of 500 mb vortex eccentricity determined by method 1 against wave one amplitude	83
3.18 Same as Figure 3.17 but for method 2	84
3.19 Scatter plot of 200 mb circumpolar vortex eccentricity against position as determined by method 1	87
3.20 Same as Figure 3.19 but for method 2	88
3.21 Spectra of 500 mb circumpolar vortex eccentricity: two days to 13 years	97
3.22 Spectra of 500 mb wave one amplitudes: two days to 13 years	98
3.23 Spectra of 200 mb circumpolar vortex eccentricity: two days to seven years	100
3.24 Spectra of 200 mb wave one amplitudes: two days to seven years	101
3.25 Spectra of 500 mb polar vortex displacements determined for method 1 along (a) 0°-180° and (b) 90°E-90°W	102
3.26 Spectra of 200 mb polar vortex displacements determined for method 1 along (a) 0°-180° and (b) 90°E-90°W	105
4.1 Two time series of monthly 500 mb circumpolar vortex eccentricity values that have been smoothed	109

Figure	Page
4.2 (a) Two time series of monthly 200 mb circumpolar vortex eccentricity values that have been smoothed	110
4.3 Histograms of monthly 500 mb polar vortex eccentricity and position	116
4.4 Histograms of monthly 200 mb polar vortex eccentricity and position	120
4.5 Spectra of monthly 500 mb circumpolar vortex eccentricity data	122
4.6 Spectra of monthly 200 mb circumpolar vortex eccentricity data	124
5.1 Spectra of daily 500 mb vortex eccentricity . . .	133
5.2 Spectra of daily 500 mb wave one amplitude data .	134
5.3 Spectra of monthly sunspot numbers	135
5.4 Spectra of seasonally averaged 30 mb zonal winds over the tropics	136
5.5 Histograms of vortex eccentricity derived from data separated according to sunspot minima and maxima .	141
5.6 Histograms of vortex position derived from data separated according to sunspot minima and maxima .	142
5.7 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase . .	146
5.8 Histograms of vortex position derived from data separated according to QBO east or west phase . .	147
5.9 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase during sunspot maxima	151
5.10 Histograms of vortex position derived from data separated according to QBO east or west phase during sunspot maxima	152
5.11 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase during sunspot minima	156

Figure	Page
5.12 Histograms of vortex position derived from data separated according to QBO east or west phase during sunspot minima	157
5.13 Four time series of vortex eccentricity deviations as determined by method 1 from monthly norms before and after explosive volcanic eruptions	166
5.14 Same as Figure 5.13 but for method 2	167

LIST OF TABLES

Table	Page
2.1 COMPARISON OF AVERAGE HEIGHTS USED TO DETERMINE CONTOURS FOR LA SEUR METHOD	39
3.1 TOTAL AVERAGES OF 500 Mb VORTEX PARAMETERS	59
3.2 SEASONAL AVERAGES OF 500 Mb VORTEX ECCENTRICITY AND WAVE ONE AMPLITUDE	60
3.3 SEASONAL AVERAGES OF 500 Mb VORTEX LOCATION . . .	61
3.4 TOTAL AVERAGES OF 200 Mb VORTEX PARAMETERS	69
3.5 SEASONAL AVERAGES OF 200 Mb VORTEX ECCENTRICITY AND WAVE ONE AMPLITUDE	70
3.6 SEASONAL AVERAGES OF 200 Mb VORTEX LOCATION . . .	71
3.7 500 Mb CORRELATION COEFFICIENTS UNFILTERED DATA .	79
3.8 500 Mb CORRELATION COEFFICIENTS SMOOTHED DATA . .	80
3.9 500 Mb CORRELATION COEFFICIENTS METHOD 1 vs METHOD 2 ECCENTRICITY	85
3.10 200 Mb CORRELATION COEFFICIENTS UNFILTERED DATA .	89
3.11 200 Mb CORRELATION COEFFICIENTS SMOOTHED DATA . .	90
3.12 200 Mb CORRELATION COEFFICIENTS METHOD 1 vs METHOD 2 ECCENTRICITY	91
3.13 DECADAL AVERAGES OF CIRCUMPOLAR VORTEX ECCENTRICITY AND WAVE ONE AMPLITUDES	93
3.14 DECADAL AVERAGES OF CIRCUMPOLAR VORTEX POSITION .	94
4.1 TOTAL AVERAGES OF MONTHLY 500 Mb VORTEX PARAMETERS	112
4.2 SEASONAL AVERAGES OF 500 Mb MEAN MONTHLY VORTEX ECCENTRICITY AND WAVE ONE AMPLITUDE	113
4.3 SEASONAL AVERAGES OF 500 Mb MEAN MONTHLY VORTEX LOCATIONS	114
4.4 TOTAL AVERAGES OF MONTHLY 200 Mb VORTEX PARAMETERS	117

Table	Page
4.5 SEASONAL AVERAGES OF 200 Mb MONTHLY VORTEX ECCENTRICITY AND WAVE ONE AMPLITUDE	118
4.6 SEASONAL AVERAGES OF 200 Mb MEAN MONTHLY VORTEX LOCATION	119
5.1 COMPARISON OF DATA BINS 500 MB MONTHLY DATA . . .	131
5.2 500 Mb VORTEX ECCENTRICITY DURING SUNSPOT MAXIMA AND MINIMA	139
5.3 500 Mb VORTEX POSITION DURING SUNSPOT MAXIMA AND MINIMA	140
5.4 500 Mb VORTEX ECCENTRICITY DURING QBO WEST AND EAST PHASE	144
5.5 500 Mb VORTEX POSITION DURING QBO WEST AND EAST PHASE	145
5.6 500 Mb VORTEX ECCENTRICITY DURING SUNSPOT MAXIMA WEST VERSUS EAST PHASE OF QBO	149
5.7 500 Mb VORTEX POSITION DURING SUNSPOT MAXIMA WEST VERSUS EAST PHASE OF QBO	150
5.8 500 Mb VORTEX ECCENTRICITY DURING SUNSPOT MINIMA WEST VERSUS EAST PHASE OF QBO	154
5.9 500 Mb VORTEX POSITION DURING SUNSPOT MINIMA WEST VERSUS EAST PHASE OF QBO	155
5.10 RESULTS OF STUDENT'S T TEST FOR SIGNIFICANCE OF VARIATION OF MEANS	161
5.11 RESULTS OF STUDENT'S T TEST FOR SIGNIFICANCE OF VARIATION OF MEANS	162
5.12 DATA BINS COMPARED USING STUDENT'S T TEST	164
5.13 CORRELATION COEFFICIENTS FROM VOLCANIC ERUPTION TIME SERIES	169

CHAPTER 1

INTRODUCTION

1.1 The Circumpolar Vortex

The eastward flow of atmospheric mass in Earth's mid-latitudes controls the general movement of weather systems in these latitudes. Due to the spheroidal shape of the earth, this eastward flow in each hemisphere revolves around a point located at or near the pole. This circulation is known as the *circumpolar vortex*; the *vortex center* is defined as the point about which cyclonic flow in the hemisphere is symmetrically distributed. On a time-averaged, constant pressure surface in the Northern Hemisphere troposphere, the circumpolar vortex appears as the area delineated by and poleward of most mid-latitude height contours. The mean 500 millibar (mb) Northern Hemisphere height field for the month of January is shown in Fig. 1.1. Examination of Fig. 1.1 suggests that the vortex center is displaced away from the North Pole, although the direction of the displacement is not immediately obvious.

A study of the circumpolar vortex was conducted by La Seur (1954). In this study, he defined the displacement of the vortex from the earth's poles as *vortex eccentricity*, a quantity that is measured in degrees of latitude. La Seur also defined the direction this displacement takes as *vortex position* (also referred to as *vortex location*), a quantity

Figure 1.1 Mean Northern Hemispheric 500 mb contours for the month of January. Heights are in decameters (From Holton, 1992).

measured in degrees of longitude eastward from the Greenwich meridian. This investigation will specifically examine temporal variations in the eccentricity and position of the circumpolar vortex in the Northern Hemisphere. As such, values of circumpolar vortex eccentricity will refer to displacements from the North Pole.

The flow of air in the circumpolar vortex (hereafter, polar vortex) reaches its maximum speed in a narrow band called the jet stream. As shown by the thermal wind equation, the jet stream is accompanied by strong temperature gradients separating cold polar air from warm tropical air (Holton, 1992). Variations in the shape and strength of the polar jet and vortex are caused by longitudinal and latitudinal thermal contrasts in the Northern Hemisphere, as well as by large variations in topography such as the Rocky Mountains and Himalayas. The thermal contrasts are caused by differences in albedo and other land-sea interactions formed by the distribution of continents.

The position of the polar vortex influences the generation and movement of weather systems. Since the vortex is distinguished by low heights and strong cyclonic curvature on a constant pressure surface, it seems reasonable that stormier weather will be found at mid latitudes near the longitude of the vortex position. Likewise, during periods of high eccentricity, regions located both up and downstream of the vortex center will exhibit ridging in response to the high

amplitude troughing. As an example, in Fig. 1.1, note the high latitude ridging near 150°W downstream of the strong trough along 150°E.

Short term variations in vortex position from average could affect a region's normal climate or may be indicative of climatic changes occurring on a hemispheric basis. Long term trends in vortex position may also give clues to gradual changes occurring in the earth's climate. Other investigations (discussed below) have already associated variations in climate with other parameters such as sunspot numbers and the cycle of stratospheric winds over the equator. The prevailing direction of these winds gradually changes from west to east over a period of two to three years. This variability in stratospheric winds is referred to as the quasi-biennial oscillation (QBO)¹. This investigation will determine if a relationship exists between the polar vortex and these parameters so that an alternative means of examining climatic change might become available.

1.2 Previous Studies

La Seur (1954) was the first meteorologist to conduct research into circumpolar vortex behavior. Using geometry to determine the centroid of contours on 500 and 700 mb polar

¹ In general, the QBO refers to any meteorological parameter that displays a nearly two year cycle. Here, the QBO refers to the cycle observed in stratospheric winds above the equatorial regions of the earth.

stereographic constant pressure charts, La Seur calculated polar vortex eccentricity and position during several short-term periods. He determined that periods of high vortex eccentricity tend to be associated with enhanced meridional flow up and downstream of the vortex center. This meridional enhancement in turn weakened the zonal flow of mass in the Northern Hemisphere. His examination of these periods also indicated: (1) large displacement periods averaged about a week in length and occurred primarily between October and March; (2) during periods of large displacement, the vortex position was near 180° longitude; and (3) large vortex displacements were coincident with large amplitudes of wave number one as determined by harmonic analyses of geopotential heights at 45° north latitude.

More recent investigations (Angell and Korshover, 1975, 1977a, 1978, 1985) made use of 300 mb monthly mean polar stereographic maps of the Northern Hemisphere to study variations in polar vortex area, position, and eccentricity as defined above. Angell and Korshover (1975) examined quasi-biennial variations in upper tropospheric polar vortex eccentricity. Their investigation involved comparisons between the 12-month running average 50 mb wind speed at Balboa, Canal Zone ($9^\circ\text{N } 75^\circ\text{E}$) and the 12-month running average of 200 mb vortex eccentricity. The results indicated that during the period 1963-1972, vortex eccentricity was about 0.5° greater during periods when the 50 mb equatorial

wind had reached maximum westerly flow than in periods of maximum easterly flow. Correlations between the two time series produced a value of 0.79 at the 99% confidence level.

Angell and Korshover (1977a) also conducted the first investigations detailing long-term polar vortex variations at the 300 mb level. They examined trends and quasi-biennial variations during the period 1963-1975. The investigation demonstrated a tendency for the annual average vortex to be located 1.5° - 2° latitude from the north pole in quadrant 90° E- 180° . During this same period, the average position of the polar vortex during spring and summer was determined for each year and was found to occur in all quadrants of the Northern Hemisphere, generally within 1° - 2° latitude from the north pole. Seasonally averaged fall and winter locations fell between 2° - 6° latitude from the north pole, exclusively in quadrant 90° E- 180° . These results agree with the limited study of La Seur (1954), and suggest that the largest vortex displacements occur during fall and winter.

Angell and Korshover (1977a) examined quasi-biennial variations in vortex location. These investigations were conducted by taking the difference between annual and seasonal vortex displacement values from the overall mean and comparing with 50 mb equatorial winds variations. They found that when the period of the QBO cycle was close to three years, there was a tendency for the vortex center to be displaced 0.5° towards the Eastern Hemisphere parallel to the 90° E- 90° W axis.

Correlations between circumpolar vortex location and surface temperatures in the United States were also examined by Angell and Korshover (1977a). These correlations revealed a tendency for displacements toward the 180th meridian to be associated with warmer temperatures in winter and fall but cooler temperatures in summer. Based on these results, Angell and Korshover expressed optimism that seasonal-foreshadowing predictions of gross climatic regimes might eventually be attempted from QBO-vortex parameter values. Angell and Korshover (1977a) noted that during the mid 1970's, circumpolar vortex areas were contracting and vortex locations were steadily moving towards the Eastern Hemisphere. They suggested that should these trends continue, winter temperatures in the United States would be relatively warmer during the winter of 1976-1977. They did, however, qualify their prediction by noting that these trends might be partially offset by expected quasi-biennial fluctuations in hemispheric temperatures.

A follow-up paper (Angell and Korshover, 1978) indicated that during the winter of 1976-1977, the circumpolar vortex had, in fact, reversed trends seen in the mid 1970's. The vortex shifted back towards the Western Hemisphere and it's area expanded significantly. This areal expansion coincided with a mid-latitude tropospheric temperature about 0.5°C below average. Angell and Korshover believed this abrupt reversal in circumpolar vortex trends could be partially explained by

variations in equatorial stratospheric zonal winds. Additional studies of seasonally-averaged vortex parameters and 50 mb winds showed a tendency for large eccentricity values to occur a season or two after a west wind maximum. The polar vortex also tended to be displaced further into the Eastern Hemisphere near the time of west wind maximum.

Angell and Korshover (1985) examined the relationship between polar vortex parameters and occurrences of El Niño as determined by changes in eastern Pacific sea surface temperatures (SST). The relationship between vortex location and occurrences of El Niño appears to be rather ambiguous. During several El Niño episodes they reported a displacement towards 90°W. In others this displacement was directed towards 90°E, while in still others (including the strong event of 1982-1983) there was a distinct tendency for displacement toward the 180th meridian. It should be noted that the analysis methods used by Angell and Korshover allowed them to determine positions only along the axes 0°-180° and 90°E-90°W. Thus, there may be significant error in the vortex locations calculated in all of their investigations. Because of this, the authors were not able to determine if the findings reflected differences in vortex displacement due to the strength of SST increase, or to problems with the method of determining vortex locations.

Finally, Angell (1992) investigated relations between the 300 mb polar vortex and patterns in equatorial SST, QBO and

sunspot numbers. This investigation built upon the research conducted by Angell and Korshover (1978) by investigating polar vortex area by quadrants rather than as a whole. The findings indicate that there is a good tendency for the vortex to be expanded into the quadrant 90°W - 180° during the same season as an El Niño occurrence. The expanded vortex in this quadrant suggests a displacement of the vortex center toward the Pacific Ocean during periods of elevated eastern Pacific equatorial SST. In addition, Angell found that vortex areas as a whole tended to be expanded during times of sunspot minima and contracted during sunspot maxima. However, he found that during periods when the 50 mb equatorial wind was from the east, the polar vortex tended to be expanded, regardless of the sunspot number.

These results of Angell (1992) seem to agree with those of Labitzke and Van Loon (1990) who investigated the occurrences of major midwinter warmings of the stratospheric Northern Hemisphere during QBO west wind maxima. Their findings indicate that sudden warmings tend to occur only during sunspot maxima. They also found statistically significant correlations between increasing sunspot numbers and middle tropospheric geopotential height rises when the data was grouped according to direction of the 30 mb equatorial winds (ie, the QBO).

Burnett (1993) investigated circumpolar vortex area as a tool in monitoring and understanding climate change.

Burnett's work was restricted to winter time monthly averaged vortex area measurements for the period between 1946 and 1989. This investigation is noteworthy primarily due to the utilization of digital information on CD-ROM which allowed the author to easily measure polar vortex area within a desired region. By utilizing this regional analysis approach, Burnett was able to demonstrate that during periods when the entire vortex is expanded in area, the specific areas over western North America and eastern Europe are contracted. In contrast, the areas over the central Pacific and eastern North America expand during these periods. Since the center of the polar vortex would by definition tend to be displaced towards the areas of expansion and away from the areas of contraction, we can visualize that the vortex center is displaced in a direction that bisects the angle between the two lobes of the expanded vortex.

In summary, several previous investigations of the circumpolar vortex have been conducted with the following limitations: La Seur (1954) analyzed daily vortex eccentricity values at 500 and 700 mb during several periods marked by large displacements. These periods ranged from a week to several months in length during the early 1950's. Angell and Korshover (1977a, 1978, 1985) determined seasonal averages of 300 mb eccentricity between 1963 and 1975 using monthly averaged data. Angell (1992) expanded this data base to include the late 1970's and 1980's, but continued to use

monthly averaged data. Thus, these investigations used dissimilar analysis techniques, different height data, and different time series. As such, an analyses of polar vortex displacement and position over a long term period, making comparisons between atmospheric levels, and using similar analysis techniques is required.

1.3 Goals of the Current Investigation

The goal of this study is to expand upon the work of La Seur (1954) by using an extensive database of daily and monthly averaged geopotential height data to calculate time series of vortex parameters. This investigation will also examine the relationships between these vortex parameters and other meteorological parameters, including sunspot numbers and quasi-biennial variations in the equatorial 30 mb zonal wind. The primary focus of this investigation will be to address implications for forecasting climatic variability based on circumpolar vortex position and the interaction of the vortex with the aforementioned meteorological parameters. While addressing this main topic, the following questions will also be addressed: 1) Is there a particular method that best measures vortex eccentricity and position, and shows correlation with other meteorological parameters? 2) Is there a particular atmospheric level at which vortex measurements exhibit better correlations with these parameters?

CHAPTER 2

METHODS AND ANALYSES

2.1 Data Source

The data used in this investigation is the National Meteorological Center (NMC) grid point data set on CD-ROM, produced by the Department of Atmospheric Sciences at the University of Washington. These data were derived from NMC operational daily and monthly averaged analyses on a 1,977-point octagonal grid with a horizontal resolution of 380 kilometers. Knox et al. (1988) criticized the reliability of these data for investigating middle-tropospheric climate change. Specifically, Knox et al. addressed changes in methods of NMC data assimilation and analyses procedures that took place in 1960 and 1962. According to Gustafson (1962) these changes introduced errors into low-latitude analyses (15° - 25° N). To minimize the risk of errors being introduced into the analyses, Knox et al. (1988) recommended eliminating data points at latitudes less than 25° N. For the purposes of this investigation, therefore, the analysis of the circumpolar vortex relies primarily on geopotential height fields at latitudes north of 40° N. As such, the danger of error being introduced into the analyses should be minimal.

Digitized geopotential height data is interpolated to a 5° latitude x 5° longitude grid encompassing the Northern

Hemisphere. This interpolation was accomplished by a FORTRAN program supplied by the University of Washington along with the data set. Height data unpacked by this program is placed into a formatted, 14x72 point ASCII file in which the latitudinal points are incremented at 5° intervals from 20° to 85° latitude and longitude points are incremented eastward from 0° to 355° (5°W) at 5° intervals.

The 500 mb height data used in the analyses consists of daily and monthly 12Z data between January 1, 1946 and December 31, 1984, a total of 14,245 days or 468 months. Similarly, the 200 mb height field data consists of daily and monthly 12Z data between January 1, 1963 and December 31, 1984, a total of 8,035 days or 264 months. There were several instances of missing daily data, generally on the order of one or two days, throughout the records. The missing data for these days was linearly interpolated from the existing data. Specifically, there were 155 instances of missing daily data at 500 mb and 127 at 200 mb. This is equivalent to 1.09% and 1.57% of the total data series at 500 and 200 mb, respectively.

2.2 Calculation of Vortex Parameters

Two procedures were used to calculate vortex eccentricity and position using adaptations of: (a) the method used by La Seur (1954); and (b) the method used by Burnett (1993). These procedures were used to determine whether the polar vortex is

best defined by measuring the centroid of several mid-latitude height contours, as was done by La Seur, or the centroid determined by the location of the polar jet stream, in the manner of Burnett. These differences may be subtle, because although the flow of the polar jet as a rule parallels geopotential height contours, it often crosses these contours depending on the steepness of the height gradient, thermal contrasts, and synoptic scale phenomena.

2.2.a METHOD 1: Mid-Latitudinal Average

The method used by La Seur (1954) will be the first to be evaluated and will henceforth be referred to as "method 1". Method 1 calculates the circumpolar vortex location based on the average of three locations, each determined from the centroid of a single geopotential height contour at mid-latitudes. The height contours used are given by the mean geopotential height at latitudes 40°N , 45°N , and 50°N ². The method used in this investigation will differ from La Seur's in that we will be using digitized data to numerically calculate vortex parameters, whereas La Seur relied upon a polar stereographic constant pressure chart to visually determine these properties.

² Since we are working with digitized data, these height contours will not necessarily be equivalent to those contours observed on a typical 500 mb chart (for example, 5640 meters).

La Seur (1954, Section 3) gives the expressions for the coordinates for the centroid of a curve as:

$$\bar{x} \approx \frac{\sum_i x_i R_i}{\sum_i R_i} \quad (1)$$

and

$$\bar{y} \approx \frac{\sum_i y_i R_i}{\sum_i R_i} \quad (2)$$

where (x_i, y_i) are the coordinates of an increment of arc length (Δl) and R_i is the radius in degrees of latitude from the north pole. When applied to a closed height contour in a plane polar coordinate system, $\bar{x}$ is the displacement in degrees of latitude from the North Pole along the axis 0° - 180° (positive toward 0°) and $\bar{y}$ is the displacement along the axis 90° E- 90° W (positive toward 90° E). The summation of i is taken from longitudes 0° to 355° where the increment is 5° of longitude. Use of the plane polar coordinate system with coordinates (R_i, λ_i) necessitates transformation of the equations, giving:

$$\bar{x} \approx \frac{\sum_i R_i^2 \cos \lambda_i}{\sum_i R_i} \quad (3)$$

and

$$\bar{y} \approx \frac{\sum_i R_i^2 \sin \lambda_i}{\sum_i R_i} \quad (4)$$

where λ_i is measured in degrees longitude from Greenwich, and R_i remains distance from the North Pole in degrees of latitude.

An example of how this method is applied to a polar stereographic projection is shown in Fig. 2.1. When working with digitized data, this process is carried out by FORTRAN code which works in the following manner: For each longitude, the height values for each pair of grid points, starting at 85°N and 80°N, are evaluated to determine if the desired height contour value falls between these points. For example, suppose we are attempting to determine the centroid of the 5640 meter height contour at $\lambda_i = 0^\circ$, and the height values at 65°N and 60°N are 5610 and 5670 meters, respectively. In this situation, the FORTRAN program will determine the height gradient between 65° and 60° to be 60 meters per 5° of latitude. The program assumes that the height gradient is uniform and determines the latitude where the desired height contour would occur (in this case, 62.5°). The value of R_i is then determined by subtracting 62.5° from 90° ($R_i = 27.5^\circ$). In situations where a height contour crosses a meridian more than once, the program determines the latitudes where the circumpolar flow is cyclonic and averages these two latitudes together to determine R_i . These values of R_i and λ_i are entered into equations (3) and (4) and the program increments

The Centroid Method

Figure 2.1 Illustration of method used to compute polar vortex location via centroid of height contours.

to the next longitude and repeats the process. After calculating the $\bar{x}$ and $\bar{y}$ values from these equations, polar vortex eccentricity (D) in degrees latitude is determined from:

$$D = \sqrt{\bar{x}^2 + \bar{y}^2}. \quad (5)$$

Similarly, vortex position (λ) is determined by:

$$\lambda = \arctan\left(\frac{\bar{y}}{\bar{x}}\right). \quad (6)$$

To illustrate the process of determining the vortex center, Fig. 2.2 presents the Northern Hemisphere 500 mb geopotential height field north of 20° latitude on December 29, 1952. The contour interval is 60 meters. Analysis of this height field reveals that the average geopotential heights at 40°N, 45°N, and 50°N are 5505, 5380, and 5300 meters, respectively. Contours corresponding to these three heights are shown in Fig. 2.3. The circumpolar vortex location determined by averaging the centroids of the three contours is marked with a '+'. Illustrations demonstrating the variability exhibited by the individual centroids before they are averaged will be presented in Section 2.4.

2.2.b METHOD 2: Maximum Height Gradient

We now turn our attention to the method adapted from Burnett (1993), which will hereafter be referred to as "method 2". Burnett, working under the assumption that the polar jet

December 29, 1952 - 500 mb

Figure 2.2 Northern Hemisphere 500 mb height contours above 20°N at 12Z, December 29, 1952. Tick marks represent 5° latitude.

Contours Used to Determine Vortex Location

Figure 2.3 500 mb height contours used for determining circumpolar vortex location via the La Seur method, December 29, 1952. Tick marks represent 5° latitude.

stream acted as a southern boundary to the circumpolar vortex, assumed that the core of the polar jet is located at the latitude of greatest height gradient along each longitude increment ($\Delta\lambda_1$). The maximum height gradient is found by examining geopotential height values at each gridpoint and calculating height changes between gridpoints along each meridian. After determining which gridpoints at a given longitude have the greatest geopotential height change between them, the location of the polar jet, and hence the boundary of the polar vortex, is assumed to occur midway between these two points. This latitude is then used to determine the value of R_1 in equations (3) and (4).

As an example, we will again use the geopotential height field shown in Fig. 2.2. Note the packing of contours that occurs on the equatorward side of the low situated about 55°N - 170°E . Analysis of this height field determined that the maximum geopotential height change along the 170°E meridian occurs between 35°N and 40°N . The midpoint between these two latitudes (37.5°N) is then assumed to be the latitude at which the jet stream core is located, and therefore delineates the boundary of the circumpolar vortex at this longitude. The radius (R_1) of this boundary in degrees from the North Pole along the 170°E meridian is given by:

$$R_1 = 90^\circ - 37.5^\circ = 52.5^\circ \text{ (and } \lambda_1 = 170^\circ \text{)}.$$

By connecting the points determined for each longitude, an isopleth which, theoretically, delineates the boundary of

the circumpolar vortex is formed. (One should note that these points will not necessarily be at any one geopotential height; see Fig. 2.4.) This isopleth is then used to determine the centroid of the polar vortex as outlined in Section 2.2.1

2.2.c La Seur Method Using Wave Number One Height Field

La Seur (1954) established that wave number one amplitudes have a high correlation with circumpolar vortex eccentricity. To illustrate this relationship, the height field for December 29, 1952 was filtered to eliminate wave numbers greater than one via fast fourier transforms (FFT) and the results plotted in Fig. 2.5a. Similar filtering was conducted to eliminate waves other than two, three, and four with the resulting height fields being presented in Figs. 2.5b, 2.5c, and 2.5d for comparison. Note that the height fields derived from wave numbers two, three, and four are symmetric about the north pole, while the field derived from wave number one is asymmetric. Thus, it is only wave number one that contributes to vortex eccentricity. The phase of wave number one greatly contributes to vortex position as well. However, this variable is influenced by other wave numbers as well.

To further illustrate the dependence of vortex eccentricity on the amplitude of wave number one, the following investigation was conducted. Methods 1 and 2 were utilized to analyze the Northern Hemisphere 500 mb height

Location of Maximum Height Gradient

Figure 2.4 Centroid formed by connecting points of maximum height change along each meridian from height field of December 29, 1952. Tick marks represent 5° latitude.

(a) Wave Number One

(b) Wave Number Two

(c) Wave Number Three (d) Wave Number Four

Figure 2.5

Height fields composed of (a) mean and wave number one only; (b) mean and wave number two; (c) mean and wave number three; and (d) mean and wave number four. Note the asymmetry present in (a). Tick marks represent 5° latitude.

fields during the 72 day period from October 10 to December 20, 1951. Polar vortex eccentricity was determined before and after filtering to eliminate wave numbers greater than one from the height field. The two time series of vortex eccentricity determined by method 1 are presented in Figs. 2.6a and 2.6b. It is apparent that, although there are some differences, the time series of eccentricity values determined from the wave number one height field is essentially the same as that determined from the unfiltered height field. Correlation of these two time series yielded a coefficient of 0.88, a value that is significant when the test for significance of linear correlation coefficients is performed (Panofsky and Brier, 1968). A third time series of polar vortex eccentricity was calculated after filtering the height field to remove only wave number one. Although the results are not presented here, eccentricity values in the time series were greatly reduced. Eccentricity values were generally less than 1° , although they were not equal to zero, as had been expected. These values apparently represent the degree of error that is present in the analyses methods and are caused by many diverse factors. A primary reason for this error may be in the method's inability to determine the north to south component of wave number one. Meridional decompositions of this sort require the analyses of Hough functions, which are carried out spherically. This type of analysis is impossible to carry out with the data set being used in this

Figure 2.6 Time series of vortex eccentricity determined by La Seur method using unfiltered height field; (a) using height field with wave numbers greater than one filtered out (b).

investigation. Other factors affecting the degree of error include the accuracy of data in the height fields, the interpolation of data points during FFT analyses, and round-off errors during computer analyses.

When the height field was analyzed by method 2, the degree of correlation between the time series determined from the original height field and the height field based upon wave number one was only 0.38, a value that is not significant. The time series of vortex eccentricity values determined from the height field after filtering to remove wave number one was again greatly reduced, but is not equal to zero. These results give confirmation that polar vortex eccentricity reflects variations in the amplitude of wave one. They also indicate that analyses by method 1 adequately reflects these variations, although method 2 does not perform as well.

2.3 Analysis Methods

Time series of daily 500 mb vortex eccentricity and position were calculated for the period January 1, 1946 to December 31, 1984. Similarly, 200 mb vortex parameters were calculated for the period January 1, 1963 to December 31, 1984. Time series of wave one amplitudes were also calculated at each pressure level. These times series were smoothed by a 360-day running mean, plotted, and examined to determine trends in the data. Statistical parameters of daily 500 and 200 mb vortex eccentricity, position and wave number one

amplitudes in the height field were calculated. These statistical parameters included means and standard deviations calculated for total and seasonal periods. Histograms were also plotted to determine the mode of vortex eccentricity and position. Finally, the power spectra of daily vortex eccentricity and position were calculated to seek regularly occurring signals within the data. Daily vortex parameter analyses will be presented in Chapter 3.

Mean monthly height data was also available from the NMC data set. Therefore, similar analyses were performed using this data in order to make direct comparisons with the results of Angell and Korshover (1975, 1977a, 1978, 1985) and to expand upon these previous investigations. These results were also compared to those calculated from daily data to determine if significant differences occurred between the two data bases. The results of monthly averaged polar vortex parameter analyses and comparisons with daily data will be presented in Chapter 4.

Parameters determined from 500 mb monthly averaged analyses were examined to look for signals that might be associated with the QBO or the sunspot cycle. Further investigations of vortex parameters and their relationship with sunspot numbers and/or the QBO were performed by separating the data into various bins, as was done by Labitzke and van Loon (1990). These bins were determined according to sunspot maxima or minima, QBO east or west phase, and the

various combinations of these parameters (e.g. QBO east phase during sunspot minima). Data from the separate bins were analyzed statistically and the results compared against the total monthly statistical results, the results from the other data bins, and results from previous investigations, including Labitzke and van Loon (1990) and Angell (1992). Finally, vortex eccentricity before and after volcanic eruptions was examined using a method known as the superposed epoch. The results of these various investigations will be presented in Chapter 5. Conclusions and recommendations for further work will be presented in Chapter 6.

2.4 Verification

Prior to analyzing the full forty year time period, comparisons were conducted with the findings of La Seur (1954) as well as those of Angell and Korshover (1985). These comparisons were conducted to verify that this investigation could duplicate the results of previous investigations, and therefore build confidence in the analyses. La Seur found that at the 500 mb level, large values of eccentricity tended to be associated with displacement toward the 180th meridian. Figure 2.7a shows vortex locations determined by La Seur for the period October 10 through December 20, 1951. Daily geopotential height data for this time period was analyzed by method 1 and the results are shown in Fig. 2.7b. Both figures show a distinct tendency for the largest values of

Vortex Locations: 10/10/51-12/20/51

Figure 2.7

(a) Summary of 500 mb polar vortex locations determined by La Seur for the period October 10-December 20, 1952 (From La Seur, 1954). (b) Summary of 500 mb polar vortex locations determined by computerized centroid method for the same period.

eccentricity to occur when the vortex is located toward longitude 180° . There are obvious differences in the pattern of vortex locations, implying that the results of method 1 are not identical to those of La Seur. However, this was not unexpected since La Seur determined vortex locations by visual inspection of constant pressure charts and some variations would naturally result. With these differences in mind, it appears that method 1 compares well with the analyses performed by La Seur.

Verifying Angell and Korshover's (1985) results proved to be more problematic. Angell and Korshover (1975, 1977a, 1978, 1985) calculated vortex locations by measuring the area within a seasonally designated height contour on a 300 mb polar stereographic plot. This investigation did not have access to 300 mb data, so the 200 mb level was chosen for this verification study because it was closer to 300 mb than any other pressure level available. Polar vortex locations were determined from monthly averaged 200 mb geopotential height fields for two time periods: January through December, 1972, and January, 1982 through December, 1983. These periods were chosen for examination because the research of Angell and Korshover (1985) indicated that they demonstrated distinct differences in polar vortex eccentricity. Vortex displacement during 1972 was minimal, while large displacements occurred during 1982 and 1983. This latter period coincided with a strong El Niño event, and is further distinguished by a

distinct tendency for displacement toward Japan. Figure 2.8 illustrates seasonal deviations of the 300 mb vortex center from the average seasonal locations, as determined by Angell and Korshover³. Vortex deviations during the period 1982-1983 (8 seasons) are connected by a bold line with arrowheads.

Vortex locations from monthly averaged 200 mb geopotential height fields were determined by an equal area technique that approximated the method used by Angell and Korshover. This technique consisted of equally bisecting the area enclosed by a designated height contour on a plane polar constant pressure chart. One bisection line would be drawn parallel to 0° - 180° and a second would parallel 90° E- 90° W. The point where these two lines intersected marked the location of the polar vortex. The resulting mean monthly vortex locations, and an average location for each of the periods of study are plotted in Figs. 2.9 and 2.10. For these same periods, we also calculated vortex locations using method 1. These results are shown in Figs. 2.11 and 2.12, and both sets of results were compared with the results of Angell and Korshover (Fig. 2.8). Note that in Fig. 2.8, 180° is at the top of the figure and 90° E is to the right, while the rest of the figures in this investigation are rotated counter-clockwise.

³ For example, an average location for all winters in the period is computed. The plot shows the deviation of a given winter's vortex center from this seasonal average.

Figure 2.8 Seasonal 300 mb polar vortex locations as determined by Angell and Korshover. Locations for the period 1982-1983 are connected by a bold line with arrowheads (From Angell and Korshover, 1985).

Figure 2.9 Monthly averaged 200 mb vortex locations as determined by equal area method, 1972. Average location marked by asterisk.

Figure 2.10 Monthly averaged 200 mb vortex locations as determined by equal area method, 1982-1983. Average location marked by asterisk.

Figure 2.11 Monthly averaged 200 mb vortex locations as determined by La Seur method, 1972. Average location marked by asterisk.

Figure 2.12 Monthly averaged 200 mb vortex locations as determined by La Seur method, 1982-1983. Average location marked by asterisk.

Vortex displacements determined by the equal area method and by method 1 agree favorably with those determined by Angell and Korshover. The results of both methods show smaller displacement values for the 1972 period when compared to 1982-1983. There is a distinct displacement towards quadrant 90°E - 180° during the 1982-1983 period. Since there is a considerable spread of individual points in Figs. 2.9-2.12, these qualities are best observed in the average vortex locations, which are also plotted.

There is, however, a discrepancy between vortex locations determined by method 1 and those determined by the equal area method. Vortex locations determined by method 1 tend to be displaced further into quadrant 90°E - 180° than those determined by equal areas. Recall from section 2.2.a that three separate vortex locations were found using the centroid of the height contour as determined by averaging the geopotential height field at 40°N , 45°N , or 50°N latitude. Table 2.1 presents the mean heights at 40°N , 45°N and 50°N latitude for each month of the 1982-1983 period. Using these individual height contours, vortex locations for the three mean latitudinal heights were determined and the results plotted in Figs. 2.13, 2.14, and 2.15. Table 2.1 also shows the height contour used by the equal area method. Vortex locations were determined by method 1 using this height contour and the results are presented in Fig. 2.16.

TABLE 2.1

COMPARISON OF AVERAGE HEIGHTS (IN METERS)
USED TO DETERMINE CONTOURS FOR LA SEUR METHOD
WITH HEIGHT SPECIFIED BY EQUAL AREA METHOD

MONTH	40°N	45°N	50°N	SPECIFIED
1-82	11690	11535	11400	11760
2-82	11675	11531	11410	11760
3-82	11751	11607	11473	12000
4-82	11862	11750	11653	12000
5-82	12005	11890	11782	12000
6-82	12160	12023	11910	12120
7-82	12294	12180	12082	12120
8-82	12329	12210	12074	12120
9-82	12213	12087	11957	12000
10-82	12046	11905	11760	12000
11-82	11874	11715	11559	12000
12-82	11786	11631	11479	11760
1-83	11697	11557	11424	11760
2-83	11599	11464	11367	11760
3-83	11680	11562	11472	12000
4-83	11753	11630	11532	12000
5-83	12008	11867	11750	12000
6-83	12137	12006	11907	12120
7-83	12310	12190	12085	12120
8-83	12344	12237	12120	12120
9-83	12233	12080	11922	12000
10-83	12082	11930	11744	12000
11-83	11858	11699	11571	12000
12-83	11738	11582	11456	11760

Figure 2.13 Monthly averaged 200 mb vortex locations determined by La Seur method utilizing mean 40° latitudinal height contour, 1982-1983. Average location marked by asterisk.

Figure 2.14 Same as Figure 2.13, but utilizing mean 45° latitudinal height contour.

Figure 2.15 Same as Figure 2.13, but utilizing mean 50° latitudinal height contour.

Figure 2.16 Same as Figure 2.13, but utilizing height contour used in equal area method.

Note that the locations determined by the equal area method (Fig. 2.10) have the same average location as those in Fig. 2.16, although there is a larger degree of scatter in the locations derived by using the equal area method. It is apparent that vortex locations determined by method 1 while using the contour determined from the 40° latitude mean height most closely approximate those determined by the equal area method. They are also similar to those determined by the method 1 while using the contour specified by the equal area method. Inspection of Table 2.1 reveals that the mean height determined for 40°N most closely approximates the equal area height contour, as we would expect from our figures. The average heights at 45°N and 50°N are generally lower. Vortex locations determined from lower height contours show greater variation and tend to be further offset toward Japan and the Pacific. This appears to be consistent with typical height fields (See Fig. 1.2) in which there is greater variation in contour geometry near the pole than at mid-latitudes.

In summary, the results of our verification study indicate that there is good agreement between our analyses and the results shown by La Seur (1954) for the period October 10 through December 20, 1951 and by Angell and Korshover (1985) for the periods 1972 and 1982-1983. Vortex displacements determined by method 1 tend to have larger values than the equal area method, and are offset toward the Pacific. These variations are consistent and can be explained by the higher

latitude height contours used by method 1. Therefore, we are confident that the differences in average vortex locations shown in Figs. 2.9 and 2.11 (and Figs. 2.10 and 2.12) arise from our application of the centroid technique using higher latitude contours. This should be kept in mind when analyzing results for the entire time period.

Results determined from our equal area method tend to show more scatter than those using the centroid technique, and also tend to show more scatter than Angell and Korshover's results (1985). This scatter could be due to any number of reasons, ranging from inconsistencies in the plotting programs which drew the charts to errors in transposing the height contours designated for analyses by Angell and Korshover from 300 mb to 200 mb. The equal area technique used by Angell and Korshover also incorporated smoothing of the height contours at 30° intervals of longitude. This smoothing process was not incorporated into our approximation of the equal area method and could represent a substantial variation in the results.

CHAPTER 3

RESULTS OF DAILY ANALYSES

3.1 Overview

In order to complete the main objective of this investigation, an expansion of the work performed by La Seur (1954), time series of vortex eccentricity and position were generated from the analyses of daily 500 and 200 mb height data. As an example, Fig. 3.1 presents the time series of daily 500 mb vortex eccentricities generated by the method adapted from Burnett (1993); hereafter, referred to as method 2 (see Section 2.2.b). This figure illustrates the widely varying values of eccentricity which were observed on a daily basis at both 500 and 200 mb. Close examination of this time series reveals an annual oscillation of displacement values. Superimposed on the annual oscillations are higher and lower frequency perturbations which give the time series a rather chaotic appearance. Because of these large scale perturbations, the time series of vortex parameters were smoothed by a 360-day running mean. This process allows us to determine if low frequency variations and longer term trends in vortex eccentricity and position are apparent. The smoothing process removes annual and higher frequency oscillations which may overwhelm longer period signals in the data. It is possible that variations in vortex parameters

Figure 3.1 Time series of daily 500 mb circumpolar vortex eccentricity values as determined by method 2, January 1, 1946 through December 31, 1984.

caused by more erratic and transitory stimuli, such as volcanic eruptions, might also be identified. Smoothed time series of vortex eccentricity, position and wave one amplitudes are presented in section 3.2.

Statistical measures were used to determine the average position and location of the polar vortex, and to give a comprehensive picture of typical variations in these parameters. Means and standard deviations of vortex eccentricity and position, and the maximum hemispheric wave number one amplitude were calculated for both pressure levels. Seasonal averages and standard deviations were also calculated and the results compared to those of Angell and Korshover (1977a). Histograms of vortex eccentricity and position were plotted to determine the distribution and mode of these parameters. Additionally, correlation coefficients were calculated between vortex eccentricity and position; between eccentricity and wave number one amplitudes; and between the eccentricity values calculated by the different methods. Correlations were calculated for raw daily data, and for data that had been smoothed by a 360-day running mean. These correlations were used to statistically verify connections between the vortex parameters and to evaluate differences that arise from the different methods of analysis. By assessing these values using daily and smoothed data we are able to ascertain the existence of high frequency correlations (from daily data) as well as longer-term correlations (from smoothed

data). Statistical analyses of daily vortex parameters will be presented in Section 3.3.

Spectral analyses of vortex parameter time series are used to determine the existence of regularly occurring signals within the data. Spectral analysis of data consists of detrending, and then determining signal strength via a fast fourier transform. An important aspect of spectral analysis is that the summation of signal strengths determined in this manner equals the variance of the original time series. Furthermore, the power of each signal represents the portion of variance that is due to waves at that particular frequency. Periodicities presented in the spectral density plots range from the nyquist frequency (2 days) to approximately one third of the total time series (13 years for 500 mb data and 7 years for 200 mb data). Stull (1988) recommended this method of low frequency cutoff to allow signals within the time series to repeat at least three times in order to ensure accurate analyses. The results of vortex parameter and wave one amplitude spectral analyses are presented in section 3.4.

3.2 Time Series

3.2.a 500 Mb Eccentricity and Amplitude

Time series of 500 mb eccentricity values calculated by both methods, and smoothed by a 360-day running mean are presented in Fig. 3.2. It should be noted that smoothing was also performed using 30- 90- and 180-day running means. For

Figure 3.2 Time series of 500 mb circumpolar vortex eccentricity values that have been smoothed by a 360-day running mean.

the purposes of this investigation, the elimination of annual and higher frequency oscillations was found to be preferable in that longer period signals, which may be related to climatic variations, became more apparent. Hereafter, a time series that has been smoothed by a 360-day running mean shall be referred to simply as 'smoothed'. In Fig. 3.2, the smoothed values generated by method 1 (adapted from the La Seur method, see Section 2.2a) fall roughly between 3° and 6° , while those generated by method 2 are between 5° and 9° . Examination of Fig. 3.2 reveals an apparent trend toward greater displacement values later in the time series for both methods 1 and 2.

A smoothed time series showing the maximum wave number one amplitude found between 25° and 85° in the 500 mb Northern Hemisphere was also constructed and the results plotted in Fig. 3.3. This plot appears similar to the series of method 2 eccentricities plotted in Fig. 3.2. Various features are common to both plots, including an initial increase in values to a distinct peak in the early-mid 1950's (~3500 days) and a sharp dip in values during the mid 1960's (~7500 days).

3.2.b 200 Mb Eccentricity and Amplitude

Time series of 200 mb eccentricity values smoothed by a 360-day running mean are presented in Fig. 3.4. Recall that the time series at 200 mb starts in 1963. As such, the time scales on 200 mb figures are different than those for 500 mb

Figure 3.3

Time series of 500 mb maximum hemispheric wave one amplitude values that has been smoothed by a 360-day running mean.

Figure 3.4

Two time series of 200 mb circumpolar vortex eccentricity values that have been smoothed by a 360-day running mean. Numerical labels at left of each series corresponds to method.

figures. The series of values generated by method 1 falls between 3° and 4° , while those generated by method 2 are between 4° and 7° . Although these displacement values are slightly less than those at 500 mb, the general trends and patterns displayed by each method compares well with it's 500 mb counterpart in Fig. 3.2. We note that there is less high frequency variability in the time series generated from 200 mb data. The trend of 200 mb vortex eccentricity determined by both methods appear to indicate a slow increase in displacement values much like those at 500 mb.

The smoothed time series of 200 mb maximum wave one amplitude is presented in Fig. 3.5. As was the case at 500 mb, this series shows some correspondence with the time series of eccentricity values generated by method 2. There is also a good correspondence with the time series of maximum wave one amplitudes generated at 500 mb.

3.2.c 500 Mb Vortex Locations

The smoothed time series of 500 mb longitudinal positions generated by methods 1 and 2 are presented in Fig. 3.6. Time has been plotted along the ordinate and increases toward the bottom of the plot. Longitude has been plotted along the abscissa from 90° to 270° (ie 90°E to 90°W). The time series of vortex locations show low amplitude oscillations about the mean position with no apparent trends occurring.

Figure 3.5 Time series of 200 mb maximum hemispheric wave one amplitude values that has been smoothed by a 360-day running mean.

Figure 3.6 Time series of 500 mb vortex locations that have been smoothed by a 360-day running mean as determined by method 1 and method 2.

3.2.d 200 Mb Vortex Locations

Circumpolar vortex longitudinal positions generated by methods 1 and 2 from 200 mb height data and smoothed by a 360-day running mean are presented in Fig. 3.7. Note that the 200 mb vortex positions are located further west than those at 500 mb. This result was expected and clearly reflects the westward tilt that typically occurs with increasing height in baroclinic disturbances. Even with the shift, trends in vortex position appear somewhat similar to those plotted for the 500 mb level and there are features common at both pressure levels.

3.3 Statistical Analyses

3.3.a 500 Mb Eccentricity and Amplitude

Means and standard deviations of 500 mb vortex eccentricity, location and wave one amplitudes are presented in Tables 3.1, 3.2, and 3.3. Overall histograms of eccentricity and position for the 500 mb level are shown in Fig. 3.8. Histograms of vortex eccentricity and position during the winter and summer months are presented in Figs. 3.9 (method 1) and 3.10 (method 2).

Circumpolar vortex eccentricity average values (Table 3.1) vary from 4.09° for Method 1 to 6.98° for Method 2. The average maximum amplitude of wave number one is 144.44 meters. The variation in vortex eccentricity values between the methods is illustrated in Figs. 3.8a & b. There is a distinct

Figure 3.7 Time series of 200 mb vortex locations that have been smoothed by a 360-day running mean as determined by (a) method 1 and (b) method 2.

TABLE 3.1
TOTAL AVERAGES OF 500 Mb VORTEX PARAMETERS

METHOD	RADIUS OF ECCENTRICITY (degrees)		LONGITUDINAL POSITION (degrees east of Greenwich)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	4.09	2.28	181	36.81
Method 2	6.98	3.63	206	40.51
Wave One Amplitude (meters)	144.44	50.12		

TABLE 3.2
SEASONAL AVERAGES OF 500 Mb VORTEX ECCENTRICITY
AND WAVE ONE AMPLITUDE
(degrees)

S E A S O N	METHOD 1		METHOD 2		WAVE ONE AMPLITUDE (meters)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	5.32	2.56	7.56	3.96	177.3	51.11
SPRING	4.44	2.27	7.29	3.65	145.1	44.17
SUMMER	3.12	1.78	6.81	3.63	114.9	37.25
FALL	3.63	1.75	6.45	3.17	141.1	46.43

TABLE 3.3
SEASONAL AVERAGES OF 500 Mb VORTEX LOCATION
(degrees east of Greenwich)

S E A S O N	METHOD 1		METHOD 2	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	175	36.89	186	41.11
SPRING	192	40.30	202	43.58
SUMMER	182	39.75	260	42.00
FALL	180	42.43	204	43.17

Figure 3.8 Histograms of 500 mb circumpolar vortex eccentricity and position determined by method 1 (a) and (c); method 2 (b) and (d).

Figure 3.9 Histograms of 500 mb circumpolar vortex eccentricity and position determined by method 1 for winter (a) and (c); and summer months (b) and (d).

Figure 3.10 Histograms of 500 mb circumpolar vortex eccentricity and position determined by method 2 for winter (a) and (c); and summer months (b) and (d).

tendency for displacement values to tail toward higher values in both methods, a common feature for quantities that possess a lower bound. Displacement values generated by Method 1 for the 500 mb level are primarily less than 10° of latitude with a distinct mode occurring between 3° and 4° . Method 2 eccentricity values display a primary mode between 4° and 5° , with a slight dip in frequency between 5° and 6° before another peak occurs between 6° and 7° .

The seasonal values of eccentricity and wave one amplitudes are presented in Table 3.2. For the purposes of this investigation, winter is December, January, February and summer is June, July, August. Wave one amplitudes and circumpolar vortex displacements vary by season with the maximum values occurring during winter. Minimum average seasonal values of eccentricity for method 1 occurred during the summer, but method 2 displacements were at an average minimum during the fall. The histograms of vortex eccentricity determined by method 1 exhibit a distinct tendency for values to drop during the summer (Fig. 3.9b). However, this tendency is much less distinct when vortex eccentricity is determined by method 2 (Fig. 3.10b). The results determined from both methods agree relatively well with those reported by La Seur (1954), although his results indicated only that larger values of eccentricity tended to occur during the "colder season" which he considered to be anytime between October and March. One discrepancy is noted

between the results for method 1 and those of previous investigations during the fall and spring. Specifically, method 1 values for spring (March, April, May) tend to be greater than those for fall (September, October, November). This differs from the results of La Seur (1954) as well as from those of Angell and Korshover (1977a), each of whom found larger values in the fall rather than spring. Another important difference is seen in the range of seasonal values. Both of the methods used in this investigation show larger eccentricity values during spring and summer than do those reported by Angell and Korshover. The average winter displacements found by method 1 coincide with those of Angell and Korshover, although method 2 average winter displacements remain larger. This may be due to the analysis of daily data, while Angell and Korshover (1977a) used mean monthly data as well as a different technique. For comparison purposes, seasonal averages were also calculated from mean monthly data and the results are presented in Chapter 4.

3.3.b 500 Mb Vortex Locations

Average longitudinal positions of the circumpolar vortex at 500 mb (Table 3.1) varied from about 181° (179°W) for method 1 to 206° (154°W) for method 2. Examination of Fig. 3.8b indicates that the overall modal position tends to be over the Pacific Ocean and near the mean position, an indication of symmetric distribution. Seasonal means of

vortex location are presented in Table 3.3. Histograms of seasonal vortex position (Figs. 3.9b and 3.10b) are highly symmetric during the winter months; vortex locations determined by both methods 1 and 2 tend to be located in or closest to the Eastern Hemisphere (0° - 180°) during this season. Seasonally averaged vortex locations determined by method 2 tend to be displaced further into the Western Hemisphere (180° - 360°) during the summer, as is apparent from Fig. 3.10b.

Between the methods, there are large differences in vortex position during the summer months, relative to the other seasons. This discrepancy is most likely a reflection of the tendency for vortex positions to show more variation during the spring and summer months, as was reported by Angell and Korshover (1977a). The position of the 500 mb circumpolar vortex determined by methods 1 and 2 also appears to be displaced westward when compared to the results of Angell and Korshover (1977a, Figs. 3 and 6). This difference is due to the westward tilt of waves with height and is made apparent by the difference in pressure levels used in the analyses (500 mb versus 300 mb used by Angell and Korshover).

3.3.c 200 Mb Eccentricity and Amplitude

Means and standard deviations of 200 mb vortex eccentricity, position and wave one amplitude were determined for the 21 years of data and the results are presented in

Tables 3.4, 3.5, and 3.6. Histograms of overall vortex eccentricity and position are presented in Fig. 3.11. Histograms of eccentricity and position during winter and summer months are presented in Figs. 3.12 (method 1) and 3.13 (method 2). Mean values of 200 mb eccentricity (Table 3.4) range from 3.47° for Method 1 to 5.65° for Method 2 and are less than those at 500 mb. The average maximum amplitude of wave number one is 188.38 meters. As seen in Fig. 3.9a, the mode for displacement values generated by method 1 occurs between 2° and 3° while method 2 displacements occur most frequently between 4° and 5° .

Seasonal means of eccentricity and wave one amplitude are presented in Table 3.5. As expected, vortex eccentricity values determined by both methods, along with wave one amplitudes, are largest during the winter and smallest during the summer. This, of course, is in agreement with the results from the 500 mb level and with those of Angell and Korshover (1977a). Seasonal histograms indicate that method 1 again shows a sharp contrast between winter and summer values (Fig. 3.12a). The histograms of method 2 eccentricity values during winter and summer also exhibit differences at the 200 mb level (Fig. 3.13a), although this was not the case at 500 mb (Fig. 3.10a). As demonstrated by Tables 3.2 and 3.5, at both the 500 and 200 mb level, the pattern of seasonal eccentricity averages determined by method 2 are in agreement with the results of Angell and Korshover (1977a).

TABLE 3.4

TOTAL AVERAGES OF 200 Mb VORTEX PARAMETERS

METHOD	RADIUS OF ECCENTRICITY (degrees)		LONGITUDINAL POSITION (degrees east of Greenwich)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	3.47	1.97	167	45.53
Method 2	5.65	3.11	138	43.39

TABLE 3.5
SEASONAL AVERAGES OF 200 Mb VORTEX ECCENTRICITY
AND WAVE ONE AMPLITUDE
(degrees)

S E A S O N	METHOD 1		METHOD 2		WAVE ONE AMPLITUDE (meters)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	4.83	2.17	7.31	3.44	237.7	68.09
SPRING	3.41	1.93	4.83	2.98	174.8	54.82
SUMMER	2.80	1.62	4.49	2.33	149.0	38.13
FALL	3.02	1.42	6.15	2.75	192.6	59.79

TABLE 3.6
SEASONAL AVERAGES OF 200 Mb VORTEX LOCATION
(degrees east of Greenwich)

S E A S O N	METHOD 1		METHOD 2	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	144	39.08	137	46.54
SPRING	181	43.04	161	45.70
SUMMER	246	36.94	103	38.92
FALL	150	42.38	151	45.75

Figure 3.11 Histograms of 200 mb circumpolar vortex eccentricity and position determined by method 1 (a) and (c); method 2 (b) and (d).

Figure 3.12 Histograms of 200 mb circumpolar vortex eccentricity and position determined by method 1 for winter (a) and (c); and summer months (b) and (d).

Figure 3.13 Histograms of 200 mb circumpolar vortex eccentricity and position determined by method 2 for winter (a) and (c); and summer months (b) and (d).

3.3.d 200 Mb Vortex Locations

Mean 200 mb vortex locations tended to occur further to the west than those at 500 mb and were in better agreement with the results of Angell and Korshover (1977a). As seen in Table 3.4, position values were 138°E for method 2 and 167°E for method 1. The histograms of overall vortex locations (Fig. 3.9b) indicate that the modal positions for methods 1 and 2 are more asymmetric than at 500 mb. However, there is still a tendency for the modal position to coincide somewhat with the mean.

Table 3.6 indicates that the greatest displacement into the Eastern Hemisphere (103°E) was found for method 2 locations during the summer months. Method 1 locations were displaced furthest into the Eastern Hemisphere during the winter (144°E). The greatest seasonally averaged displacement into the Western Hemisphere for method 1 was found during the summer (114°W). In fact, a comparison of the histograms presenting 500 and 200 mb seasonal vortex positions determined by method 1, (Figs. 3.9b and 3.12b) appears to indicate an eastward tilt with height during the summer months. However, this is not the case with method 2 (Figs. 3.10b and 3.13b). Seasonally averaged vortex locations determined by method 2 were confined to the Eastern Hemisphere. The greatest average displacements toward the Western Hemisphere occurred during the spring months (161°E).

3.3.e 500 Mb Correlations

Scatter plots of circumpolar vortex displacement and position are presented in Figs. 3.14 and 3.15. These figures show that when eccentricity values are greatest, vortex position is generally about 150° - 180° . These results are in good agreement with those of La Seur (1954, Figs. 21 and 22). The plots are also useful in that the preferred position of the circumpolar vortex appears as a darker area. These scatter plots display ellipsoidal areas of maximum vortex occurrence near the 180^{th} meridian.

Correlation coefficients of daily vortex eccentricity and position are presented in Table 3.7. By testing the significance of linear correlation coefficients it has been determined that a correlation whose absolute value is greater than 0.04 is 99% accurate (Panofsky and Brier, 1968). Table 3.8. presents correlation coefficients of eccentricity and position for data that has been smoothed by a 360-day running mean. Because of the smoothing process, each data point is essentially linked to the 180 data points that fall before and after it. Therefore, when discussing smoothed data, we have 99% confidence in the accuracy of a correlation coefficient whose value is 0.39 or greater; while a coefficient of 0.31 is accurate at the 95% level.

Correlations of eccentricity with the 0° - 180° and 90° E- 90° W axes were also calculated and are presented in Tables 3.7 and 3.8. Correlations would be positive were the vortex to be

Figure 3.14 Scatter plot of 500 mb circumpolar vortex eccentricity against position as determined by method 1.

Figure 3.15 Same as Figure 3.14 but for method 2.

TABLE 3.7

500 Mb CORRELATION COEFFICIENTS
 COLUMN 1: ECCENTRICITY VS LONGITUDINAL POSITION
 COLUMNS 2 & 3: ECCENTRICITY VS MAJOR AXES
 COLUMN 4: ECCENTRICITY VS WAVE ONE AMPLITUDE

(Non-Smoothed Data)

METHOD	LONGITUDE	0°-180°	90°E-90°W	WAVE ONE AMPLITUDE
Method 1	0.39*	-0.87*	-0.01	0.47*
Method 2	0.18*	-0.47*	-0.34*	0.29*

* 99% Accurate

TABLE 3.8

500 Mb CORRELATION COEFFICIENTS
 COLUMN 1: ECCENTRICITY vs LONGITUDINAL POSITION
 COLUMNS 2 & 3: ECCENTRICITY vs MAJOR AXES
 COLUMN 4: ECCENTRICITY vs WAVE ONE AMPLITUDE

(Data Smoothed by 360-Day Mean)

METHOD	LONGITUDE	0°-180°	90°E-90°W	WAVE ONE AMPLITUDE
Method 1	0.29	-0.93*	-0.08	0.42*
Method 2	-0.04	-0.63*	-0.42*	0.67*

* 99% Accurate

displaced toward 0° or 90°E , and negative when displaced towards the 180° or 90°W . Examination of Table 3.8 reveals that methods 1 and 2 each show a distinct tendency for the polar vortex to be displaced toward the Pacific Ocean (180°) when eccentricity values increase. Furthermore, both values are 99% accurate.

Correlations between Northern Hemisphere wave number one maximum amplitudes and the degree of circumpolar vortex eccentricity were also calculated. This phase of the investigation was motivated by the findings of La Seur (1954) who reported a positive correspondence (based on scatter plots) of wave one amplitude versus vortex displacement. The results of La Seur are reproduced here in Fig. 3.16. Similar scatter plots have been plotted for the two methods and are presented in Figs. 3.17 and 3.18. These figures indicate, and correlations which are accurate at the 99% level confirm (Table 3.7), that eccentricity increases as wave one amplitudes increase. Close examination of these figures also seems to indicate that displacements away from the North Pole do not occur until wave one amplitudes approach 100 meters. While these results may reflect some type of lag response factor, it is more likely that we are seeing some measure of the inaccuracies inherent in our analyses methods. Correlation values derived from daily data were 0.29 (method 2) and 0.47 (method 1). These values are not as large as those found for the test case during the verification study

Figure 3.16 Scatter plot of vortex eccentricity against wave one amplitude (from La Seur, 1954).

Figure 3.17 Scatter plot of 500 mb vortex eccentricity determined by method 1 against wave one amplitude.

Figure 3.18 Same as Figure 3.17 but for method 2.

(see Section 2.2.c), although there is no obvious reason why this should be so. When the data is smoothed by a 360-day running mean, there is correlation at the 99% accuracy level (0.67) between wave one amplitudes and displacement values derived from method 2 (Table 3.8). While these correlation values are less than were expected, they are still significant and indicate that the similarities observed between the time series of smoothed wave one amplitude and eccentricity (Figs. 3.2 and 3.3) are authentic.

Correlations were also calculated between the eccentricity values derived by the two methods. These results are presented in Table 3.9. There is a moderate tendency for methods 1 and 2 to show correspondence on a daily basis (0.43). Long term eccentricity trends determined by methods 1 and 2 should show better correlation (0.61). This values is accurate at the 99% level.

TABLE 3.9

**500 Mb CORRELATION COEFFICIENTS
METHOD 1 vs METHOD 2
ECCENTRICITY**

UNFILTERED DATA	DATA SMOOTHED BY 360-DAY RUNNING MEAN
0.43*	0.61*

* 99% Accuracy

3.3.f 200 Mb Correlations

Scatter plots of circumpolar vortex eccentricity and longitudinal position (Figs. 3.19 and 3.20) indicate that at the 200 mb level, greatest displacement occurs between 140°E and 180° . The scatter plots generated from methods 1 and 2 show similar results to those at 500 mb (Figs. 3.14 and 3.15). However, the areas of maximum occurrence and offset are located in the quadrant 90°E - 180° , about 30° to 80° west of similar areas found from 500 mb data.

Daily and smoothed values of circumpolar vortex eccentricity and position were correlated against each other and the results presented in Tables 3.10 and 3.11. There were approximately 8,035 data points used to determine coefficients for the daily data. This volume of data implies that correlation values whose absolute value is greater than 0.05 will be accurate at the 99% level when testing for significance of linear correlation coefficients (Panofsky and Brier, 1968). Absolute values of correlations determined from smoothed data are accurate at the 99% level if greater than 0.51, while absolute values greater than 0.41 are accurate at the 95% level.

For the daily data values, only method 1 shows any large degree of correlation, that being a tendency to be displaced towards the Pacific Ocean when values increase. When polar vortex parameters were smoothed, method 2 exhibited a very good correlation for vortex displacements along the 0° - 180°

Figure 3.19 Scatter plot of 200 mb circumpolar vortex eccentricity against position as determined by method 1.

Figure 3.20 Same as Figure 3.19 but for method 2.

TABLE 3.10

200 Mb CORRELATION COEFFICIENTS
 COLUMN 1: ECCENTRICITY VS LONGITUDINAL POSITION
 COLUMNS 2 & 3: ECCENTRICITY VS MAJOR AXES
 COLUMN 4: ECCENTRICITY VS WAVE ONE AMPLITUDE

(Non-Smoothed Data)

METHOD	LONGITUDE	0°-180°	90°E-90°W	WAVE ONE AMPLITUDE
Method 1	0.29*	-0.70*	0.35*	0.56*
Method 2	0.27*	-0.55*	0.35*	0.40*

* 99% Accuracy

TABLE 3.11

200 Mb CORRELATION COEFFICIENTS
 COLUMN 1: ECCENTRICITY VS LONGITUDINAL POSITION
 COLUMNS 2 & 3: ECCENTRICITY VS MAJOR AXES
 COLUMN 4: ECCENTRICITY VS WAVE ONE AMPLITUDE

(Data Smoothed by 360-Day Mean)

METHOD	LONGITUDE	0°-180°	90°E-90°W	WAVE ONE AMPLITUDE
Method 1	-0.07	-0.20	0.35	0.42**
Method 2	0.00	-0.72*	0.46**	0.50**

* 99% Accuracy
 ** 95% Accuracy

axis (0.72) and moderate tendencies for displacements towards the Western Hemisphere (0.46). Correlations between daily eccentricity values and wave one amplitudes indicate a fair to good tendency for the 200 mb polar vortex to be displaced from the North Pole as amplitudes increase. In fact, for both methods 1 and 2, this relationship is stronger at the 200 mb level than at the 500 mb level. Smoothed 200 mb eccentricity values derived from method 1 exhibited the same correlation as those at 500 mb, but correlation coefficients for method 2 were less than those at 500 mb.

When 200 mb eccentricity values determined by the two methods are correlated, we find there is some correspondence between daily values (0.41, see Table 3.12). When the data is smoothed by a 360-day running mean, this value is virtually the same (0.40).

TABLE 3.12

**200 Mb CORRELATION COEFFICIENTS
METHOD 1 vs METHOD 2
ECCENTRICITY**

UNFILTERED DATA	DATA SMOOTHED BY 360-DAY RUNNING MEAN
0.41*	0.40

* 99% Accuracy

3.3.g Decadal Averages

Knox et al. (1988) reported evidence of a climate shift during the early to mid 1960's in 500 mb Northern Hemispheric mean geopotential heights. The evidence for this shift included different means, trends, and degrees of variability with an abrupt transition. The time series of 500 mb vortex data was examined to determine if decadal changes in polar vortex parameters indicated that a climatic shift was apparent. Daily data for the period 1950-1979 was separated according to decade of occurrence and analyzed to determine means and standard deviations for the separate decades.

Average values of 500 mb vortex eccentricity for the periods 1950-59, 1960-69 and 1970-79 are presented in Table 3.13. These values indicate that the maximum average vortex eccentricity determined by method 1 occurred during the 1950's (4.32°). Vortex displacements dropped during the 1960's to 4.02° before rebounding slightly in the 1970's to 4.05° . In contrast, method 2 eccentricity values increased slightly from 7.04° in the 1950's to 7.11° in the 1960's and then dropped to their minimum value of 6.88° in the 1970's. Wave one amplitudes also exhibited maximum values during the 1960's (151.61 meters) but, in this case, minimum values were recorded during the 1950's (142.33).

Decadal averages of vortex position showed more variation according to method (Table 3.14). Method 1 vortex positions moved steadily eastward over the 30 year period, from 179°E to

TABLE 3.13

DECADAL AVERAGES
OF CIRCUMPOLAR VORTEX ECCENTRICITY
AND WAVE ONE AMPLITUDES
(degrees)

METHOD	1950's	1960's	1970's	OVERALL
Method 1	4.32	4.02	4.05	4.09
Method 2	7.04	7.11	6.88	6.98
Wave One Amplitude (meters)	142.33	151.61	144.59	144.44

TABLE 3.14

DECADAL AVERAGES
OF CIRCUMPOLAR VORTEX POSITION
(degrees east of Greenwich)

METHOD	1950's	1960's	1970's	OVERALL
Method 1	179	182	184	181
Method 2	207	208	204	206

176°W (184°). Method 2 positions moved 1° eastward between the 50's and 60's, from 154°W (206°) to 152°W (208°), but jumped 4° westward during the 1970's to 156° (204°).

Statistical analyses of vortex eccentricity and position on a decadal basis indicates that long-term variations of these parameters have been occurring. The student's T test for significance of variation of means was used to compare the average values of vortex eccentricity and position for each decade. The significance level for variations determined by this test is 95%. The findings indicate that the average eccentricity and position values determined by method 1 from 1950's data varies from the overall mean and from the mean values calculated for the 1960's and 1970's. There is no significant variation between the 1960 and 1970 decadal averages of vortex eccentricity and position. Method 2 eccentricity values during the 1970's were found to vary from the overall average and from the 1960's average. No other significant variations were determined from method 2 vortex parameters. The average value of wave one amplitude during each of the three decades significantly varies from the other decades and from the overall average. These results indicate that decadal averages of wave one amplitude, along with vortex eccentricity and position, show some significant variations. However, there does not appear to be enough information to determine the existence of a specific climatic change during the period under investigation.

3.4 Spectral Analyses

3.4.a 500 Mb Eccentricity and Amplitude

Power spectral density graphs of circumpolar vortex eccentricity parameters are presented in Fig. 3.21. As would be expected, there is a discrete signal occurring at a period of one year with both methods. A one year signal clearly dominates vortex eccentricities determined by method 1 (Fig. 3.21a). Higher frequency signals are also present, but signal strength is far less than for the dominating frequency. In contrast, method 2 eccentricity values are dominated by the higher frequencies (Fig. 3.21b) with considerable power between 2 and 90 days. This signature appears to contain *blue noise*; that is, signals with frequencies higher than the nyquist frequency of two days have been aliased and appear as lower frequencies. It should also be noted that in this case the one year signal is not very large. One explanation for the dominance of higher frequencies could be related to the use of one line connecting points of maximum height change when determining vortex parameters with method 2. There is generally a large amount of scatter in the vortex location when using only one centroid (see Section 2.4, Verification). It is speculated that the higher frequency noise was filtered out by the averaging process used in method 1.

Northern Hemisphere 500 mb wave one amplitudes show a power spectrum (Fig. 3.22) that is very similar to method 1 eccentricities. The power spectral density is dominated by a

Figure 3.21 Spectra of 500 mb circumpolar vortex eccentricity: two days to 13 years. Determined for (a) method 1 and (b) method 2.

Figure 3.22 Spectra of 500 mb wave one amplitudes: two days to 13 years.

one year signal with accompanying higher frequency signals of much lesser power.

The spectral analyses of vortex eccentricity and wave one amplitudes generated results in which signals with periods greater than one year are not readily apparent. In order to examine the strength of these lower frequency signals, spectral analysis was performed on time series that had been smoothed by a 360-day running mean. The results of this analysis were compared to power spectra derived from sunspot numbers and QBO data and will be presented in Chapter 5.

3.4.b 200 Mb Eccentricity and Amplitude

The spectral analysis of method 1 derived displacements of the 200 mb circumpolar vortex is presented in Fig. 3.23a. This figure resembles the power spectrum generated from 500 mb method 1 eccentricity (Fig. 3.21a). However, the strength of the one year signal at 200 mb is about half that present at 500 mb. The power spectrum of method 2 eccentricity at 200 mb is presented in Fig. 3.23b. In this figure, the one year signal of method 2 eccentricity is dominant but the higher frequency signals increase in strength as we approach the nyquist frequency. Comparisons between Fig. 3.23b and it's 500 mb counterpart (3.21b) reveal that the one year signal delineated by method 2 is much stronger in the upper troposphere than in the middle troposphere. The power spectrum of 200 mb wave one amplitudes is presented in Fig.

Figure 3.23 Spectra of 200 mb circumpolar vortex eccentricity: two days to seven years. Determined for (a) method 1 and (b) method 2.

3.24 and does not appear to differ significantly from that at 500 mb (Fig. 3.22). However, it should be noted that the one year signal is 20% more powerful at 200 mb than at 500 mb. These results indicate that there are definite variations in the one year signal that are observed between the middle and upper troposphere. However, these variations are not consistent between the two methods, nor is the reason for these variations apparent.

3.4.c 500 Mb Vortex Location

To further understand the signals present in the time series of circumpolar vortex location, spectral analyses of displacements along the axes, 0° - 180° and 90° E- 90° W, were performed. Analyses of method 1 vortex locations along these axes are presented in Figs. 3.25a (0° - 180°) and 3.25b (90° E- 90° W). Displacements between the Pacific Ocean and Greenwich, England (ie along 0° - 180°) show a strong one year signal. This appears quite similar to the 500 mb method 1 eccentricity power spectrum (Fig. 3.21a). In fact, this result should not be unexpected since it has been established that the favored direction of method 1 vortex displacements is at the 180^{th} meridian. Displacements between the Eastern and Western Hemisphere do not exhibit any dominant periodicity. Similar results were determined for method 2, however, the results are not presented.

Figure 3.24 Spectra of 200 mb wave one amplitudes: two days to seven years.

Figure 3.25 Spectra of 500 mb polar vortex displacements determined for method 1 along (a) 0°-180° and (b) 90°E-90°W. Two days to 13 years.

3.3.d 200 Mb Vortex Location

Once again, spectral analyses of polar vortex locations at 200 mb were performed for displacements relative to the major axial components. The spectral density plots for method 1 are presented in Figs. 3.26a and 3.26b. These figures display a very powerful one year signal for displacements along both axes. In particular, the one year signal for displacements along 90°E - 90°W is much stronger than it's 500 mb counterpart (Fig. 3.25b). This is apparently a result of the preferred 200 mb vortex position at 200 mb being located within the quadrant 90°E - 180° . The results of spectral analyses of displacements along these axes for locations derived from method 2 are similar and not presented.

3.5 Summary

Statistical results indicate that eccentricity values determined by the two methods are generally greater than those determined by La Seur or Angell and Korshover. However, method 1 displacement values during winter are comparable with these earlier findings. The pattern of seasonal averages of vortex eccentricity is consistent with earlier investigations, in that greatest displacements occurred during winter. Discrepancies were noted, however, in that larger displacement values were found for the fall rather than spring, as was previously determined by Angell and Korshover (1977a). These discrepancies may be insignificant in that values during both

Figure 3.26 Spectra of 200 mb polar vortex displacements determined for method 1 along (a) 0°-180° and (b) 90°E-90°W. Two days to seven years.

these seasons fall between those of winter and summer. It is speculated that the margin for error inherent in the analyses technique (previously mentioned in Section 2.2.c) may contribute to this reversal. At the 200 mb level, the pattern of seasonal eccentricity averages determined by method 2 appear to be consistent with the results determined by Angell and Korshover (1977a). Seasonally averaged 500 mb vortex locations determined by methods 1 and 2 are consistently displaced towards the Western Hemisphere when compared to the results of Angell and Korshover, who analyzed vortex locations at the 300 mb level. However, seasonally averaged locations determined at the 200 mb level are more in keeping with their results.

Daily and smoothed (by 360-day running mean) vortex eccentricity data determined by methods 1 and 2 at both pressure levels consistently show a distinct tendency for the polar vortex to be directed towards the Pacific Ocean when displacement values increase. There is also a positive correlation between daily and smoothed values of vortex eccentricity and wave one amplitudes for all methods and at both pressure levels. On a daily basis, this relationship is stronger at the 200 mb level than at the 500 mb level. However, for smoothed data, the opposite relation holds.

CHAPTER 4

RESULTS OF MONTHLY ANALYSES

The NMC CD-ROM data set also contains mean monthly geopotential height data from the 500 and 200 mb pressure levels. These data were analyzed to determine mean monthly circumpolar vortex parameters for the same time periods as were used for the daily data. This phase of the investigation was performed in order to make direct comparisons with the results of Angell and Korshover (1975, 1977a, 1978, 1985) who used mean monthly data sets to determine vortex parameters.

Vortex eccentricity data was smoothed by a 12-month running mean, plotted and examined to determine long-term trends. Statistical analyses were used to examine vortex eccentricity and position for the total time period, and also after separation of the data according to season. Finally, spectral analyses were used to search for regularly occurring temporal variations in the data. Our results were then compared to the results from the daily data analysis and those of previous investigations. We have also expanded upon the work of Angell and Korshover by including mean monthly data at separate pressure levels and including data prior to 1963. Comparisons between mean monthly and daily data were also performed in order to determine if the averaging of

geopotential height data significantly affected the analyses of vortex parameters.

In Chapter 5, the mean monthly vortex parameters will be used to look for the existence of hypothesized teleconnections between vortex behavior and other physical phenomena such as sunspot cycles, the QBO, and volcanic eruptions. An examination of the smoothed time series of vortex eccentricity is presented in section 4.1, statistical results for monthly vortex parameters are presented in section 4.2, and the results of spectral analyses are in section 4.3.

4.1 Time Series Of Monthly Eccentricity

Vortex parameters at the 500 and 200 mb pressure levels were calculated using methods 1 and 2. The time series of vortex eccentricity at each level was smoothed by a 12-month running mean and plotted. The results are presented in Figs. 4.1a and 4.2a, respectively. For comparison purposes, the smoothed time series of daily data at each pressure level are also included as Figs. 4.1b and 4.2b. The time series of mean monthly vortex displacements appear quite similar to the daily time series at both 500 and 200 mb (Figs. 3.2 and 3.4). These results indicate that the basic patterns and trends in eccentricity are reflected in both the daily and monthly time series.

Figure 4.1 (a) Two time series of monthly 500 mb circumpolar vortex eccentricity values that have been smoothed by a 12-month running mean. (b) Same, but for daily data smoothed by 360-day running mean (Fig. 3.2).

Figure 4.2 (a) Two time series of monthly 200 mb circumpolar vortex eccentricity values that have been smoothed by a 12-month running mean. (b) Same, but for daily data smoothed by 360-day running mean (Fig. 3.4).

4.2 Statistics From Mean Monthly Data

4.2.a 500 Mb Data

Vortex parameters were statistically analyzed to determine their average value and standard deviations. Average values determined from 500 mb data are presented in Table 4.1. Seasonal averages of mean monthly data are presented in Tables 4.2 and 4.3. Taken as a whole, vortex eccentricity averages determined from monthly data are smaller than those derived from daily data (see Tables 3.1, 3.2, and 3.3). Specifically, the average displacement from the North Pole when using method 1 was 13% smaller, while that derived from method 2 was 3% less. In addition, the average value of 500 mb maximum wave one amplitudes determined from monthly data was 36% smaller than the average taken from daily data. The smaller values determined from mean monthly height data may be due to the temporal averaging process used by NMC. As would be expected, seasonal averages were also less than those determined from daily data. The largest average displacements occurred during the winter while the smallest were recorded in either summer or fall. These findings were in agreement with those determined from daily data.

No major differences in the average polar vortex position were found between the results of the monthly and daily data. Average locations were within 10° of longitude of those previously determined for both methods. Seasonal averages of monthly vortex positions were within 25° of those resulting

TABLE 4.1

TOTAL AVERAGES OF MONTHLY 500 Mb VORTEX PARAMETERS

METHOD	RADIUS OF ECCENTRICITY (degrees)		LONGITUDINAL POSITION (degrees east of Greenwich)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	3.57	1.74	177	32.40
Method 2	6.79	3.30	196	44.13
Wave One Amplitude (meters)	92.87	39.30		

TABLE 4.2
SEASONAL AVERAGES OF 500 Mb MEAN MONTHLY VORTEX ECCENTRICITY
AND WAVE ONE AMPLITUDE
(degrees)

S E A S O N	METHOD 1		METHOD 2		WAVE ONE AMPLITUDE (meters)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	5.04	1.62	7.10	3.00	122.50	33.29
SPRING	3.87	1.51	6.71	3.43	93.06	25.95
SUMMER	2.30	1.31	6.98	4.02	64.27	19.00
FALL	3.05	1.19	6.38	2.59	91.65	29.67

TABLE 4.3
SEASONAL AVERAGES OF 500 Mb MEAN MONTHLY VORTEX LOCATIONS
(degrees east of Greenwich)

S E A S O N	METHOD 1		METHOD 2	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	171	16.25	173	54.81
SPRING	193	23.39	202	62.11
SUMMER	163	53.81	235	79.23
FALL	174	20.09	190	33.16

from daily data. However, the standard deviations resulting from monthly vortex positions using method 2 are much larger than those resulting from daily data. This indicates that mean monthly vortex positions have greater variability than daily positions. Histograms of mean monthly 500 mb vortex eccentricity and position are presented in Fig. 4.3. The distributions deduced from monthly data are very similar to the histograms of daily vortex parameters presented in Fig. 3.8.

4.1.b 200 Mb Data

Average values determined from 200 mb data are presented in Tables 4.4, 4.5, and 4.6, while histograms are plotted in Fig. 4.4. As was the case at 500 mb, vortex eccentricity averages determined from the monthly data are smaller than those derived from daily data (see Tables 3.4, 3.5, and 3.6). In this case, the average displacements derived from methods 1 and 2 were 14% and 24% less, respectively. In addition, the average value of 200 mb maximum wave one amplitudes was 29% smaller than the average taken from daily data.

The average polar vortex positions found by method 2 exhibited large variations from averages determined using daily data. The average position determined for the total monthly data set (99°E) is 39° west of the average determined from daily data (138°E). There was a very large deviation in the average spring vortex location resulting from method 2

Figure 4.3 Histograms of monthly 500 mb polar vortex eccentricity and position for method 1 (a) and (c); and method 2 (b) and (d).

TABLE 4.4
TOTAL AVERAGES OF MONTHLY 200 Mb VORTEX PARAMETERS

METHOD	RADIUS OF ECCENTRICITY (degrees)		LONGITUDINAL POSITION (degrees east of Greenwich)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	2.97	1.44	164	52.32
Method 2	4.31	2.48	99	47.60
Wave One Amplitude (meters)	134.35	41.77		

TABLE 4.5
SEASONAL AVERAGES OF 200 Mb MONTHLY VORTEX ECCENTRICITY
AND WAVE ONE AMPLITUDE
(degrees)

S E A S O N	METHOD 1		METHOD 2		WAVE ONE AMPLITUDE (meters)	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	4.44	1.27	6.55	2.64	172.00	44.05
SPRING	2.72	1.28	4.03	2.10	119.51	32.59
SUMMER	2.16	0.91	4.39	1.68	110.05	17.00
FALL	2.55	1.07	6.26	2.40	135.85	38.81

TABLE 4.6
SEASONAL AVERAGES OF 200 Mb MEAN MONTHLY VORTEX LOCATION
(degrees east of Greenwich)

S E A S O N	METHOD 1		METHOD 2	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
WINTER	143	12.24	103	47.00
SPRING	181	34.45	9	201.47
SUMMER	238	33.24	82	54.67
FALL	144	26.85	128	36.21

Figure 4.4 Histograms of monthly 200 mb polar vortex eccentricity and position for method 1 (a) and (c); and method 2 (b) and (d).

data as well. In this case, the position resulting from monthly data (9°E) is 152° west of it's daily data counterpart (161°). As was the case at 500 mb, the standard deviations resulting from monthly vortex positions determined by method 2 are also much larger than those resulting from daily data.

The occasionally large differences between daily and monthly values of vortex position should be borne in mind as one reviews these results. As was demonstrated in Section 2.4, we are confident that our methods reproduce the results of Angell and Korshover (1975, 1977a, 1978, 1985) when using monthly data. Similarly, our methods adequately determined daily vortex parameters when comparisons were made with the work of La Seur (1954). As such, the variations between daily and monthly vortex parameters is troubling, in that the monthly averaging of height data should not produce such drastic differences. However, this investigation was not able to pursue these questions.

4.3 Spectral Analyses Of Monthly Eccentricity

Monthly 500 mb vortex eccentricity values determined from methods 1 and 2 have been spectrally analyzed and the resulting power spectra shown in Figs. 4.5a and 4.5b. When comparing these results to those derived from daily data (Figs. 3.17a & b), one should note that the minimum resolvable frequency is now two months. The power density plot derived from method 1 is similar to it's daily data counterpart. Both

Figure 4.5 Spectra of monthly 500 mb circumpolar vortex eccentricity data analyzed by (a) method 1 and (b) method 2. Two months to 13 years.

figures show a strong peak at the frequency that corresponds to a period of one year. In general, the spectral density plots derived from monthly and daily data analyzed by method 1 are very similar. This implies that, despite differences observed in the degree of eccentricity between the two data sets, we can be confident that similar temporal variations are present for periods greater than two months. In contrast, the spectral density plot of monthly method 2 eccentricities does not exhibit a one year peak corresponding with that determined from the analyses of daily data. Again, we speculate that since method 2 uses only one height contour to determine vortex locations, higher frequency variations in eccentricity overwhelm the one year signal. However, this explanation is not certain and would require additional study. It is clear that analysis of mean monthly data by method 2 does not manifest the same temporal variations observed in daily data.

Spectral density plots of monthly 200 mb vortex displacements from the North Pole are presented in Figs. 4.6a and 4.6b (compare with Figs. 3.19a & b). In this case, both methods 1 and 2 show good agreement between the power spectra derived from daily and monthly data.

4.4 Summary

Monthly vortex eccentricity values at 500 and 200 mb are smaller than those determined from daily data. It is suggested that these variations are due to the monthly

Figure 4.6 Spectra of monthly 200 mb circumpolar vortex eccentricity data analyzed by (a) method 1 and (b) method 2. Two months to seven years.

averaging of geopotential height data by NMC. As was the case with daily data, displacements determined using method 1 were smaller than those of method 2. It should be noted that 200 mb monthly vortex displacements determined by method 1 are comparable with those determined by Angell and Korshover (1977a). When eccentricity values are averaged on a seasonal basis, they exhibit greater eccentricity during the winter and less during the summer and fall. These findings correspond well with the results presented in Chapter 3. Total and seasonally averaged vortex positions determined from daily and monthly data also correspond very well, in that there is generally less than a 25° difference between the positions determined from the two data sets. However, there is a large discrepancy in the average spring position determined from monthly and daily data at 200 mb when using method 2.

The smoothed time series of polar vortex eccentricity values determined from monthly data appear very similar to those determined from daily data. The similar trends are also reflected in the spectral analyses of monthly vortex eccentricity. There is a very good correspondence between the spectral density plots determined from monthly and daily data at both pressure levels when analyzed by method 1. Variations in the strength of the one year signal appear in the analysis of 500 mb data by method 2. In summary, although there are some differences in the vortex eccentricity values determined from monthly and daily data, it appears that temporal

variations in the data sets are similar. Furthermore, it appears that method 1 best reflects these temporal variations at both pressure levels and has the advantage of producing results comparable to those found in previous investigations.

CHAPTER 5

THE POLAR VORTEX AND CLIMATIC VARIATIONS

The final phase of this investigation is an examination of hypothesized teleconnections between 500 mb circumpolar vortex parameters and other phenomena, namely sunspots, variations in 30 mb zonal winds over the tropics (the QBO), and volcanic eruptions. Aspects of this investigation include: (1) a comparison of low frequency spectral density plots derived from vortex eccentricity and wave one amplitude with plots derived from monthly averaged sunspot numbers and seasonally averaged 30 mb zonal winds over the tropics; (2) separation of monthly averaged vortex parameters into data bins based upon sunspot number and QBO phase; (3) an examination of time series derived from deviations of vortex eccentricity from monthly norms for the twelve months before and immediately following eight separate volcanic eruptions.

Experimental procedures used in this phase of the investigation will be outlined in section 5.1. Results for the separate investigations will be presented in sections 5.2 (low frequency spectral analysis), 5.3 (separation of data according to QBO phase and sunspot number) and 5.4 (volcanic eruptions).

5.1 Experimental Procedures

Vortex eccentricity and wave one amplitude data from the 500 mb pressure level were used in this phase of the investigation. The 500 mb level was chosen primarily because of the larger data set representing a time span of nearly twice that at 200 mb. The extended time frame was considered essential to sufficiently ascertain long-term variations in the data set. For each experiment, FORTRAN programs were written to read raw data from a formatted ASCII file, process the data and write the results to an output file. These results were then imported to the MATLAB numerical processing program where further analyses was performed with the results being used to create graphs and spectral analyses plots.

5.1.a *Low Frequency Analyses Procedures*

Temporal variations with periods greater than one year are weak compared to yearly and higher frequency signals, but are nevertheless important because they could be associated with gradual changes in climate. Low frequency spectral analyses of wave one amplitudes and vortex eccentricity were performed on daily data (smoothed by a 360-day running mean) and the resulting spectral density graphs examined for periods between one and thirteen years. Low frequency peaks found by this analysis were then compared to spectral density plots derived from monthly averaged sunspot numbers and seasonally averaged QBO data to determine if they possessed similar

periods. The source for monthly sunspot data was the National Geophysical Data Center's Solar and Terrestrial Physics on-line Internet access under the listing 'Zurich monthly'. Monthly sunspot numbers observed from Zurich, Switzerland during the period 1946-1984 were taken from the full data set which includes data for the period 1749-1993. Seasonally averaged 30-mb wind data was taken from two sources; Labitzke (1982) presented data from 1953-1980, while Naujokat (1986) presented data for the period 1956-1984. These sources were combined to provide a data source of seasonally averaged 30 mb zonal winds over the tropics for the period 1953-1984. Although this data set does not encompass the full 39 year period of the polar vortex data, it proved to be sufficiently long to give an acceptably detailed spectral density plot.

5.1.b Procedures for Separation of Data

Results published by Labitzke and van Loon (1990) indicated that significant variations in 500 mb northern hemisphere height data were observed when the data was separated according to the phase of the QBO (west or east) and by sunspot number (maximum or minimum). An investigation was designed to see if similar variations were observed in polar vortex parameters. This investigation used the same sunspot numbers and 30-mb zonal winds that were used in the low frequency spectral analyses. Determination of whether or not vortex data from a particular month occurred during sunspot

minima or maxima and QBO east or west phase was made by calculating the average value and standard deviation of these parameters. Data that fell within one standard deviation from the average value was discarded. For example, during the 39 year period being examined, the average value of monthly sunspot numbers is 81.54 and the standard deviation is 37.78. During months in which the sunspot number was less than $(81.54 - 37.78) = 43.76$, polar vortex eccentricity values were separated into the bin designated sunspot minima data. Using this technique, monthly vortex data was separated into various bins based upon QBO phase and sunspot number. In doing so, eight data bins were created: sunspot max, sunspot min, QBO west, QBO east, QBO west during max, QBO west during min, QBO east during max and QBO east during min. Binning in this manner results in much smaller data sets than the overall 500 mb data set which contains 468 months. Table 5.1 presents the number of data points in each bin. Means, standard deviations and histograms of vortex eccentricity and position were then calculated from the data in each bin.

5.1.c Volcanic Eruption Procedures

Volcanic eruptions and their possible impact on vortex eccentricity were examined using a method known as the superposed epoch (Panofsky and Brier, 1965). Eight documented volcanic eruptions, in which an estimated one cubic kilometer or more of material was injected into the atmosphere, were

TABLE 5.1
COMPARISON OF DATA BINS
500 MB MONTHLY DATA

DATA BIN	NUMBER OF POINTS
Overall	468
Sunspot Maxima	126
Sunspot Minima	156
QBO West Phase	96
QBO East Phase	124
QBO West Phase - Sunspot Maxima	19
QBO East Phase - Sunspot Maxima	37
QBO West Phase - Sunspot Minima	33
QBO East Phase - Sunspot Minima	49

chosen for analysis. Vortex eccentricity for the twelve months before and after an eruption were compared to the average eccentricity value determined from the overall data set for that month. Four separate time series of deviations from the normal monthly eccentricity were created. These include: (1) the eruption of Mount Agung (March, 1963); (2) the eruption of El Chichón (April, 1982); (3) a time series which combined six separate eruptions and does not include either Agung or El Chichón; (4) a test series that uses monthly data selected from a time period in which no volcanic eruptions were recorded. The four time series of vortex

deviations from monthly norms were plotted and compared visually. Correlation coefficients were also determined from the various time series.

5.2 Low Frequency Analyses

Spectral density plots of low frequency signals (over one year) in 500 mb vortex eccentricity as determined by methods 1 and 2 are presented in Figs. 5.1a and 5.1b. The spectral density plot derived from 500 mb wave one amplitudes is presented in Fig. 5.2. Method 1 eccentricities showed peaks with periods of about 3.8 and 7.9 years. Method 2 shows peaks near 4.9 and about 3.5 years. As was the case with method 1 data, minor peaks with periods less than 2.5 years are also observed. Spectral analysis of wave one amplitudes produced peaks with periods near 2.7 and 1.7 years and a pair of peaks with periods of roughly 3.5 and 4.2 years. There is also a moderate peak near 12.5 years. However, this spectrum appears to be influenced by *red noise* which is indicative of even lower frequency signals that were not adequately resolved by the analysis.

Spectral density plots derived from spectral analyses of monthly averaged sunspot numbers and seasonally averaged values of the equatorial zonal wind at 30 mb are presented in Figs. 5.3 and 5.4. It is well known that sunspot numbers measured over the last 250 years exhibit an eleven year cycle.

Figure 5.1 Spectra of daily 500 mb vortex eccentricity analyzed by (a) method 1 and (b) method 2. One year to thirteen years.

Figure 5.2 Spectra of daily 500 mb wave one amplitude data. One year to thirteen years

Figure 5.3 Spectra of monthly sunspot numbers. Two months to thirteen years.

Figure 5.4 Spectra of seasonally averaged 30 mb zonal winds over the tropics. Six months to eleven years.

However, for the 39 year period between 1946 and 1984, a cycle of about 9.7 years prevailed. Spectral analyses of the 30 mb zonal wind over the tropics showed a strong 2.5 year cycle in the data.

Comparisons of the spectral density plots generated from wave one amplitudes and vortex eccentricity with those derived from sunspot numbers do not indicate the existence of temporal variations having a common periodicity. However, there is rough agreement in the spectral density plots calculated from wave one amplitudes with that determined from QBO data. As mentioned above, there is a strong signal with a period of 2.7 years in wave one amplitude data. There are also some smaller, nearly insignificant, peaks with periods between 2 and 3 years observed in vortex eccentricities determined from methods 1 and 2. Although the signals do not correspond exactly, it is suggested that they may be associated with QBO variations. Variations observed in the periodicity of these signals could result from the shorter time series of QBO data, differences in time steps (monthly vortex data versus seasonal QBO data), or inaccuracies resulting from the interpolation of QBO data from two separate sources into one data set.

5.3 Separation By Sunspot and QBO Phase

5.3.a Sunspot Maxima versus Minima

Averages and standard deviations of vortex eccentricity, position and wave one amplitude during sunspot maxima and minima are presented in Tables 5.2 and 5.3. Histograms are presented in Figs. 5.5 and 5.6. Examination of Table 5.2 reveals that during sunspot maxima average eccentricity determined by both methods 1 and 2 is 7% less than the overall average. During sunspot minima, average eccentricities determined by method 1 are 2% greater than the overall average while method 2 eccentricities are 4% greater. Average wave one amplitudes are nearly identical during sunspot maxima and minima, and both values exceed the overall monthly averaged amplitude by a scant two meters. This suggests that, during periods of sunspot minima and maxima, wave one amplitudes increase above the overall 39-year average. The converse of this would be that during periods when sunspot numbers are close to the long term average, wave one amplitudes are below average. The histograms of eccentricity in Fig. 5.5 reflect these differences in means; moreover, the modes appear more sharply defined when compared to the histograms for all monthly data presented in Fig. 4.3.

Average vortex positions determined by methods 1 and 2 during sunspot minima were displaced only about 1° from the overall average positions presented in Table 4.1. During sunspot maxima, the average vortex positions determined by

TABLE 5.2
500 Mb VORTEX ECCENTRICITY
DURING SUNSPOT MAXIMA AND MINIMA
(degrees)

METHOD	SUNSPOT MAXIMA		SUNSPOT MINIMA		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	3.33	1.64	3.65	1.79	3.57	1.74
Method 2	6.34	3.14	7.08	3.42	6.79	3.30
Wave One Amplitude (meters)	94.75	29.38	94.25	27.58	92.87	39.30

TABLE 5.3

500 Mb VORTEX POSITION
DURING SUNSPOT MAXIMA AND MINIMA
(degrees east of Greenwich)

METHOD	SUNSPOT MAXIMA		SUNSPOT MINIMA		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	174	33.40	178	32.96	177	32.40
Method 2	200	44.67	195	43.85	196	44.13

Figure 5.5 Histograms of vortex eccentricity derived from data separated according to sunspot minima and maxima using method 1 (a) and (c); method 2 (b) and (d).

Figure 5.6 Histograms of vortex position derived from data separated according to sunspot minima and maxima using method 1 (a) and (c); method 2 (b) and (d).

methods 1 and 2 were displaced 4° from the total average. The histograms of vortex position presented in Fig. 5.6 indicate that the modal positions determined by method 1 are more sharply defined than those of method 2 while the distribution of vortex positions for both methods tends to be uneven. Thus, although degree of eccentricity may respond to changes in sunspot number, vortex position does not.

5.3.b QBO West versus East

Average values of vortex eccentricity and position during the west and east phases of the QBO are presented in Tables 5.4 and 5.5. Histograms of these parameters are presented in Figs. 5.7 and 5.8. When the data is separated in this method, eccentricities determined by method 1 are greater than the overall average during the west phase of the QBO, and less than the overall average during the east phase. Eccentricity values determined by method 2 are larger during the east phase of the QBO than during the west phase. However, both values are greater than the overall average eccentricity value. Wave one amplitudes, in line with method 1 eccentricities, are greatest during the west phase, and average values during both east and west phases of the QBO are larger than the overall average. The histograms of vortex eccentricity reflect the differences in method 1 averages that were mentioned above. Percent frequency totals of eccentricity values determined by method 2 indicate that modal values of displacement are

TABLE 5.4
500 Mb VORTEX ECCENTRICITY
DURING QBO WEST AND EAST PHASE
(degrees)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	3.69	1.89	3.28	1.81	3.57	1.74
Method 2	7.17	3.34	7.33	3.56	6.79	3.30
Wave One Amplitude (meters)	100.8	27.61	96.4	25.67	92.87	39.30

TABLE 5.5
500 Mb VORTEX POSITION
DURING QBO WEST AND EAST PHASE
(degrees east of Greenwich)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	175	29.86	178	31.52	177	32.40
Method 2	195	47.11	204	45.33	196	44.13

Figure 5.7 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase using method 1 (a) and (c); method 2 (b) and (d).

Figure 5.8 Histograms of vortex position derived from data separated according to QBO east or west phase using method 1 (a) and (c); method 2 (b) and (d).

usually much less than 10° but significant tailing increases the average eccentricity.

Vortex positions determined by methods 1 and 2 during west QBO were displaced only slightly to the west of the total average position. During the east phase of the QBO, method 1 vortex locations were 1° east of the total average, but method 2 positions were displaced 8° eastward. Thus, we see that eccentricity responds to changes in QBO phase, but position does not.

5.3.c QBO West versus East During Sunspot Maxima

Tables 5.6 and 5.7 present average vortex parameters during periods when data was separated according to phase of the QBO during sunspot maxima. Histograms showing percentage frequency of vortex eccentricity and position are presented in Figs. 5.9 and 5.10. During sunspot maxima, the average eccentricity values determined by both methods are larger during the west phase of the QBO than the east phase. In this case, the average eccentricity values determined by methods 1 for both east and west phases are less than the overall average value. The average eccentricity value determined by method 2 is greater than the overall average during the west phase of the QBO and less than the overall average during the east phase. Average wave one amplitudes during the west phase are larger than during the east phase and both values are greater than the overall average value determined.

TABLE 5.6
500 Mb VORTEX ECCENTRICITY
DURING SUNSPOT MAXIMA
WEST VERSUS EAST PHASE OF QBO
(degrees)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	3.10	1.72	2.93	1.53	3.57	1.74
Method 2	7.35	3.72	6.61	3.34	6.79	3.30
Wave One Amplitude (meters)	103.00	22.34	100.75	21.39	92.87	39.30

TABLE 5.7
500 Mb VORTEX POSITION
DURING SUNSPOT MAXIMA
WEST VERSUS EAST PHASE OF QBO
(degrees east of Greenwich)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	171	26.22	174	39.98	177	32.40
Method 2	222	53.30	202	37.82	196	44.13

Figure 5.9 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase during sunspot maxima using method 1 (a) and (c); method 2 (b) and (d).

Figure 5.10 Histograms of vortex position derived from data separated according to QBO east or west phase during sunspot maxima using method 1 (a) and (c); method 2 (b) and (d).

and both values are greater than the overall average value determined.

Average vortex locations determined by method 1 are displaced westward from the overall average during either phase of the QBO and sunspot maxima. In contrast to this, the average locations determined by method 2 are displaced eastward during both phases of the QBO and sunspot maxima. However, with the exception of method 2 during the west phase of the QBO, these displacements are less than 10° .

5.3.d QBO West versus East During Sunspot Minima

Tables 5.8 and 5.9 present average vortex parameters during periods when data was separated according to phase of the QBO during sunspot minima. Histograms showing percentage frequency of vortex eccentricity and position are presented in Figs. 5.11 and 5.12. When eccentricity data is separated according to east and west phase of the QBO during sunspot minima, average values determined by methods 1 and 2 are larger than the overall average during the west phase. During the east phase of the QBO and sunspot minima, method 1 eccentricities are smaller than the overall average, but method 2 eccentricities are larger than the overall average. Average wave one amplitudes are larger during the west phase of the QBO than the east phase, but both values are larger than the overall average.

TABLE 5.8
500 Mb VORTEX ECCENTRICITY
DURING SUNSPOT MINIMA
WEST VERSUS EAST PHASE OF QBO
(degrees)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	4.07	1.82	3.33	1.83	3.57	1.74
Method 2	7.35	2.87	7.20	3.96	6.79	3.30
Wave One Amplitude (meters)	102.75	21.45	100.50	20.42	92.87	39.30

TABLE 5.9

500 Mb VORTEX POSITION
DURING SUNSPOT MINIMA
WEST VERSUS EAST PHASE OF QBO
(degrees east of Greenwich)

METHOD	QBO WEST		QBO EAST		OVERALL	
	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
Method 1	177	37.75	181	29.65	177	32.40
Method 2	191	50.93	208	45.76	196	44.13

Figure 5.11 Histograms of vortex eccentricity derived from data separated according to QBO east or west phase during sunspot minima using method 1 (a) and (c); method 2 (b) and (d).

Figure 5.12 Histograms of vortex position derived from data separated according to QBO east or west phase during sunspot minima using method 1 (a) and (c); method 2 (b) and (d).

During the east phase of the QBO and sunspot minima, average vortex locations determined by both methods 1 and 2 are displaced eastward of the overall average position. The average vortex location determined by method 1 during the west phase of the QBO and sunspot minima is identical to the overall average position. Vortex locations determined by method 2 during the west phase are displaced westward 5° from the overall average.

5.3.e Comparisons of QBO Phases and Sunspot Numbers

Comparisons of the values presented in Tables 5.6 and 5.8 indicate that method 1 values are larger than the overall average during west phase of the QBO and sunspot minimum, and are smaller than the overall average during west phase of the QBO and sunspot maximum. Method 1 eccentricities are also smaller than the overall average during east phase of the QBO and both sunspot maxima and minima. Method 2 average eccentricity values are smaller than the overall average during east phase of the QBO and sunspot maxima but are larger than the overall average during east phase of the QBO and sunspot minima. Method 2 average eccentricity values during both sunspot maxima and minima are larger than the overall average and equal to each other when separated according to west phase of the QBO.

Similar comparisons of the values presented in Tables 5.7 and 5.9 indicate that displacements from the overall average

position of method 1 vortex positions determined by binning are less than 6° of longitude. Method 2 average vortex positions are displaced 26° eastward from the overall average position during west phase of the QBO and sunspot maxima while they are displaced only 5° westward during west phase of the QBO and sunspot minima. During east phase of the QBO, method 2 average positions are displaced 6° and 12° eastward during sunspot maxima and minima, respectively.

5.3.f *Significance*

The average eccentricity values determined by separation of data according to QBO phase and sunspot numbers were analyzed to ascertain whether variations from the overall average and between data bins were significant. A series of 100 tests were conducted for each set of binned data using the student's T test to calculate variations between two means at the 95% significance level. In these tests, the binned data was compared to an identically sized set of data selected randomly from the entire time series. A significant variation between the two data sets would indicate that the randomly selected data set could not have the same mean value as the binned data. This further implies that the binned data is significantly different from the overall time series. A second series of tests was made in which the binned data mean was compared to a set of data selected randomly from the time series after the binned data had been removed. For example,

the data set of vortex eccentricity values during sunspot maximum and west phase of the QBO contains 19 data points. For the first series of student T tests, the mean value from this data set was compared to the means from 100 different data sets containing 19 randomly selected eccentricity values from the entire time series of 468 months. In the second phase, this same mean value was compared to the means from 100 data sets, again containing 19 randomly selected eccentricity values, this time from the time series after the binned data points had been removed. Tables 5.10 and 5.11 present the results of the student's T test to determine variations between mean values of eccentricity and wave one amplitudes from the overall mean when data is separated according to QBO phase and sunspot numbers.

Table 5.10 indicates that the data separated according to QBO phase and sunspot number exhibits virtually no significant variations from data randomly selected from the entire time series. In the case of method 1 eccentricity values during sunspot maxima and east phase of the QBO, only 31 out of 100 trials indicated a significant variation.

As would be expected, when the T test was conducted using randomly selected data points after separation of data according to QBO phase and sunspot number, the degree of significant variation increased somewhat (Table 5.11). This was especially apparent in the case of method 2 eccentricity values during sunspot maxima and east phase of the QBO. When

TABLE 5.10

RESULTS OF STUDENT'S T TEST
FOR SIGNIFICANCE OF VARIATION OF MEANS
(Data selected from entire time series)

DATA BIN	METHOD 1		METHOD 2		WAVE ONE AMPLITUDES	
	VARIATION	NO VARIATION	VARIATION	NO VARIATION	VARIATION	NO VARIATION
Sunspot Maxima	5	95	10	90	13	87
Sunspot Minima	1	99	6	94	4	96
QBO West	4	96	7	93	3	97
QBO East	14	86	9	91	5	95
QBO West - Sunspot Maxima	2	98	2	98	0	100
QBO East - Sunspot Maxima	31	69	0	100	10	90
QBO West - Sunspot Minima	12	88	4	96	12	88
QBO East - Sunspot Minima	0	100	1	99	0	100

TABLE 5.11

RESULTS OF STUDENT'S T TEST
FOR SIGNIFICANCE OF VARIATION OF MEANS

(Data selected from time series after separation of data)

DATA BIN	METHOD 1		METHOD 2		WAVE ONE AMPLITUDES	
	VARIATION	NO VARIATION	VARIATION	NO VARIATION	VARIATION	NO VARIATION
Sunspot Maxima	17	83	14	86	20	80
Sunspot Minima	2	98	3	97	3	97
QBO West	1	99	2	98	2	98
QBO East	32	68	35	65	20	80
QBO West - Sunspot Maxima	3	97	12	88	1	99
QBO East - Sunspot Maxima	24	76	46	54	27	73
QBO West - Sunspot Minima	8	92	16	84	12	88
QBO East - Sunspot Minima	2	98	6	94	2	98

the mean eccentricity value from this data bin was compared to that of randomly selected data points taken from the entire time series there were no significant variations. In contrast, Table 5.11 shows that 46 out of 100 trials indicate a significant variation at the 95 percentile level when the randomly selected data was chosen after removal of the binned data. In fact, wave one amplitudes and eccentricity values determined by both methods 1 and 2 show some degree of significant variation from the mean during sunspot maxima, during east phase of the QBO, and during east phase of the QBO at the time of a sunspot maximum. It should be noted that although there is some indication of significant differences, none of these data bins exhibits any clear cut trend toward significant variations from the overall mean.

Finally, the student's T test was used to examine the means between the various bins. For example, the bin containing data during sunspot maxima was compared to that for sunspot minima. Table 5.12 lists the data bins that were compared for significant variations, using the student's T test. These tests indicate that both wave one amplitudes and eccentricity values determined by method 1, when binned according to sunspot minima during QBO west phase and sunspot maxima during QBO east phase, show significant variation between the two data bins. There were no other significant variations found between data sets.

TABLE 5.12
DATA BINS COMPARED
USING STUDENT'S T TEST

BINS	SIGNIFICANT VARIATION ?		
	METHOD 1	METHOD 2	AMPS
Sunspot Maxima and Sunspot Minima	No	No	No
QBO West and QBO East	No	No	No
QBO West and QBO East During Sunspot Maxima	No	No	No
QBO West and QBO East During Sunspot Minima	No	No	No
QBO West During Maxima and QBO West During Minima	No	No	No
QBO East During Maxima and QBO East During Minima	No	No	No
QBO West During Maxima and QBO East During Minima	No	No	No
QBO West During Minima and QBO East During Maxima	Yes	No	Yes

These results should be compared to the results of Labitzke and van Loon (1990) who found that during the west phase of the QBO, major midwinter warmings of the Northern Hemisphere stratospheric vortex tend to occur only when the sunspot cycle is at a maximum. They also found that statistically significant correlations between the solar cycle and 'atmospheric elements' such as 500 mb Northern Hemisphere height data were found when grouped according to QBO phase. Furthermore, Labitzke and van Loon (1990) found that

correlations coefficients were of opposite sign during east and west phases of the QBO, which led to small correlations when a total time series was used.

5.4 Volcanic Eruptions and Eccentricity

Time series of eccentricity deviations from the norm before and after volcanic eruptions are presented in Figs. 5.13 and 5.14. Each figure contains four separate time series that have been smoothed using a 1-2-1 filter. Examination of these figures reveals that for all methods, there are no apparent similarities in the deviation patterns before or after an eruption. For example, the curves for deviations following Agung and El Chichón are opposed. These results could be considered as interesting, since each of these events was well documented as producing similar increases in Northern Hemisphere stratospheric temperatures (Naujokat, 1986). When these two time series are compared to the composite time series derived from six other volcanic eruptions, (including Mount Hekla [1947], Mount Lamington [1951], Mount Bezymianny [1956], Mount Taal [1965], Mount Fernandina [1968], and Mount Saint Helens [1980]), the results again indicate no apparent correspondence. Finally, comparisons of these three separate times series with another time series generated from data chosen during a period when no volcanic events were recorded show a similar lack of correspondence. As such, these results seem to indicate that vortex eccentricity is not affected by

Figure 5.13 Four time series of vortex eccentricity deviations as determined by method 1 from monthly norms before and after explosive volcanic eruptions.

Figure 5.14 Same as Figure 5.13 but for method 2.

the introduction of high silica ash into the atmosphere by explosive volcanic eruptions.

Correlations derived between the various time series are presented in Table 5.13. For 25 data points (12 months before eruption, 12 months after eruption, and month eruption occurred), a significant correlation with 1% chance of error must have an absolute value greater than 0.54. The largest correlation between two time series (-0.44) was found using the time series from Mount Agung and the composite eruptions. Therefore, neither this, nor any other correlation, is significant. More importantly, in order for the hypothesized connection to be valid, the correlation coefficients between the two time series should be positive. The highest positive correlations were between Mount Agung and the random test period using method 1 data. These statistical results confirm the conclusion suggested by the time series and indicate that monthly 500 mb vortex eccentricity is not directly affected by the introduction of high silica ash into the atmosphere by explosive volcanic eruptions.

5.5 Summary

Low frequency spectral density plots were generated by spectral analyses of 500 mb circumpolar eccentricity and wave one amplitudes. Similar plots generated from monthly sunspot data indicate that there are no shared temporal variations between these vortex parameters and sunspot variations. When

TABLE 5.13
CORRELATION COEFFICIENTS
FROM
VOLCANIC ERUPTION TIME SERIES

CORRELATION	METHOD 1	METHOD 2
Agung vs Chichón	-0.16	-0.28
Agung vs Composite	-0.44	-0.38
Chichón vs Composite	-0.03	-0.16
Agung vs Test	0.33	0.10
Chichón vs Test	-0.16	0.06
Composite vs Test	0.06	0.26

compared to a spectral density plot generated from seasonal 30 mb zonal winds over the tropics, however, there did appear to be some commonality of peaks with periods near 2.5 years.

Separation of 500 mb polar vortex eccentricity data according to sunspot number and phase of QBO indicates that for methods 1 and 2, the largest eccentricity values occur during sunspot minimum and west phase of the QBO. Minimum values of vortex eccentricity determined by methods 1 and 2 occur during sunspot maximum and east phase of the QBO. Although wave one amplitudes are not similarly influenced, they do tend to be larger than the overall monthly average during both extremes of sunspot number as well as both QBO phases.

These results suggest another discrepancy with regard to our analysis. We have already documented a positive correlation between wave one amplitudes and vortex eccentricity. Thus, we would expect that increased amplitude values in the data bins imply increased eccentricity as well. Since this is not the case, it may be that the small number of data points in each bin (see Table 5.1) has a disproportional affect on the mean values.

Variations from the overall mean were tested for significance at the 95 percentile level using the student's T test. Two separate series of 100 trials were conducted for each data bin. Each of these trials indicated that there is no conclusively significant variation between the binned data and the overall mean. However, in the case of sunspot maxima, QBO east phase and sunspot maxima during QBO east phase, there is some indication that the binned data means are approaching a significant variation from the overall mean. Comparisons of data binned according to sunspot minima during QBO west phase and sunspot maxima during QBO east phase indicated significant variation between these data bins for both wave one amplitudes and eccentricity values determined by method 1.

Separation of the polar vortex longitudinal position by sunspot number and phase indicated no large variations in position due to QBO phase or sunspot cycle. The largest average displacement from the overall average position was

observed in method 2 vortex positions during west phase of the QBO and sunspot maximum.

Finally, for each method, four time series showing deviations of monthly eccentricity from monthly eccentricity norms before and after explosive volcanic eruptions were examined. The results of this investigation indicated that two separate volcanic eruptions and a composite of six other eruptions did not generate similar responses in vortex eccentricity. From these results it was concluded that monthly 500 mb vortex eccentricity values are not affected by the introduction of high silica ash into the atmosphere by explosive volcanic eruptions.

CHAPTER 6

SUMMARY, DISCUSSION, AND CONCLUSIONS

The primary goal of the current investigation was to expand the analysis of circumpolar vortex eccentricity and location to cover the period 1946-1984 using geopotential height data. As part of this investigation, FORTRAN programs were written to access digitized geopotential height data for any time period available on the NMC CD-ROM data disk. Using these programs, daily and mean monthly 500 mb geopotential height data were gathered for the entire 39 year period. In addition, 200 mb height data were gathered for the 21 year period, 1963-1984. Additional FORTRAN programs were written to examine this data and determine the circumpolar vortex parameters of eccentricity and position, as well as maximum hemispheric wave one amplitudes. As a result, at each pressure level, two time series of vortex parameters and one time series of wave one amplitudes have been generated and examined using daily and monthly data.

Throughout the analysis process, results of statistical and spectral analyses of these parameters were evaluated to determine differences and similarities between the two methods used and pressure levels. The results were further contrasted against those published by La Seur (1954) and Angell and

Korshover (1975, 1977a, 1978, 1985). Thus, this investigation has expanded upon these earlier investigations. Specifically, La Seur (1954) found that (1) periods of large eccentricity occurred during the winter; (2) vortex positions during these periods tended to occur near 180° longitude; and (3) large periods of eccentricity were coincident with large amplitudes of wave number one in the middle troposphere. Our findings agree well with those of La Seur, and confirm that vortex eccentricity in the middle troposphere is greatest during the winter and smallest during the summer. Scatter plots and correlations of vortex eccentricity and position indicate that when largest eccentricity values occur, the vortex center is found near 180° . Finally, correlations of maximum Northern Hemisphere wave one amplitudes and vortex eccentricity values indicate that vortex displacement from the North Pole increases as wave one amplitudes increase. This is to be expected, since examination of planetary scale waves embedded in a constant pressure height field indicates that wave number one is the only wave number to affect the field's symmetry

Using the mean monthly geopotential height data, this investigation has also expanded upon the upper tropospheric investigations of Angell and Korshover (1975, 1977a, 1978, 1985). Their results also showed that seasonal variations in vortex eccentricity and position occur. Specifically, Angell and Korshover found results that were similar to those of La Seur (1954) with the largest values of eccentricity occurring

during the winter months and smallest values occurring during the summer. Seasonal variations of vortex position were also reported, with average positions occurring in the quadrant 90°E - 180° during winter months, and in all quadrants during the spring and summer. It should again be noted that Angell and Korshover analyzed vortex parameters at the 300 mb level and these positions are generally west of those found at 500 mb. Angell and Korshover (1977a) also reported marginally significant tendencies for vortex eccentricity to increase when the 50 mb equatorial wind cycle between west and east wind maxima (the QBO) was close to three years.

This investigation has found that 200 mb vortex parameters analyzed by method 1 were comparable to the results of Angell and Korshover (1975, 1977a, 1978, 1985). Some differences in the degree of eccentricity determined by method 1 and method 2 were observed. On the whole, the eccentricity values produced by method 1 were closer to those produced by the research of Angell and Korshover. Mean monthly height data also produced smaller eccentricity values than were produced from daily data. The variations in the degree of eccentricity between the two methods could be attributed to method 2 using only one isopleth to determine vortex locations. This isopleth is determined by maximum height gradients along a given meridian. It is probable that contour packing causes this isopleth to occur at higher latitudes than the mid-latitude contours used in method 1. As was noted in

section 2.4, there is greater variability in height contours at higher latitudes causing the vortex center to be defined further from the pole. The differences between daily and monthly average vortex eccentricity values appears to be caused by the temporal averaging of geopotential height data by NMC.

Very good agreement was found in the direction of greatest vortex displacements determined by both methods using daily and monthly data. In the middle troposphere (500 mb) vortex displacements were greatest near 180° , while the largest vortex displacements occurred between 90°E and 180° at 200 mb. Periodicities in eccentricity values and offsets toward the Pacific Ocean showed a strong one year signal with the largest average displacements occurring in winter. There were also some noticeable differences in vortex parameters at 500 versus 200 mb. In general, smaller eccentricity values were found at 200 mb.

Correlation of daily vortex eccentricities determined by method 1 and wave one amplitudes showed the highest correlations. However, when these time series are smoothed in order to determine long term variations, method 2 shows superior correlation with wave one amplitudes. These correlations are further confirmed in similarities between plotted time series of eccentricity and wave one amplitudes, as well as spectral density plots that display similar patterns. This indicates that studies of short term

variations in vortex eccentricity and wave one amplitudes, such as might influence the daily weather over a given region, would be best suited by using method 1. Studies that wish to concentrate on longer term variations in these parameters, such as their relation to climate change, might wish to use method 2. Further examination of the differences between the two methods may be warranted. In fact, since neither of these methods can be considered completely reliable, it would be instructive to investigate alternative methods of determining vortex locations. As an example, we might combine the best aspects of each of these methods by first determining the average height at which the maximum height gradient occurs in the height field. A single height contour with this height value could then be used to determine the centroid.

Comparisons of the spectral density plots determined from monthly and daily vortex eccentricity data indicates that there are no substantial differences in the spectra derived from these two data sets. These results imply that, despite variations observed in the average value of vortex eccentricity determined from daily and monthly data, similar temporal variations appear in both data sets. Therefore, either data set can be used to determine long term variations in vortex parameters.

Finally, the relationship between vortex parameters and other meteorological phenomena such as volcanic eruptions, sunspot numbers and quasi-biennial variations in the

equatorial 30 mb zonal wind were examined to determine the existence of correlations between the phenomena. The separation of data according to sunspot number and QBO phase suggest other avenues for study. Vortex eccentricity determined by method 1 and wave one amplitudes each show significant variations between sunspot minima-west QBO and sunspot maxima-east QBO, as was found by Labitzke and van Loon (1990). The apparent agreement of this investigation's findings with the results of Labitzke and van Loon suggests that these variations may be more than a coincidence.

Other interesting results were observed in wave one amplitudes separated according to sunspot number and QBO phase. Specifically, the average amplitude determined from each of these data bins is larger than the overall average. Although it was not found to be significantly different according to the student's T test, the largest average amplitude was found during periods of sunspot maxima-west QBO. Labitzke and Van Loon (1990) reported that during the west phase of the QBO, major midwinter warmings of the polar stratosphere, which are associated with amplification of planetary waves in the troposphere and stratosphere, occur only during sunspot maxima. Labitzke and Van Loon have also reported variations in stratospheric polar temperatures and tropospheric heights based on separation of data along similar lines. However, they did not feel that their results were definitive.

Examination of vortex eccentricity for the 12 months before and after eight separate volcanic eruptions indicates that there are no apparent changes in vortex eccentricity associated with these events. Although Naujokat (1986) found that the eruptions of Mount Agung and El Chichón resulted in similar increases in Northern Hemisphere stratospheric temperatures, correlations of the eccentricity time series derived from these events showed no apparent relation.

In conclusion, this investigation has determined that variations in vortex eccentricity determined by methods 1 and 2 show short and long term variations. The primary short term variation is an annual cycle in vortex eccentricity in which larger values occur during the winter and smaller values during the summer. When 500 mb vortex eccentricity values are large, the position tends to be near 180° . Spectral analyses of daily and mean monthly eccentricity data indicates that the averaging process used by NMC does not appear to substantially alter temporal variations present in the data set, although eccentricity values are altered. Finally, the results of this investigation appear to agree with previous findings by Labitzke and van Loon (1990) that variations in atmospheric parameters are observed when data is separated according to sunspot number and QBO phase.

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