6.3 TRENDS IN THE 1949–2000 NORTHERN HEMISPHERE CIRCUMPOLAR VORTEX AND CLIMATE CHANGE IMPLICATIONS

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1. INTRODUCTION

Much attention has been given for more than a decade to the possibility that human activity is causing changes in climate. An ongoing debate is the discrepancy between the observed surface warming and the lack of warming in satellite-based temperature measurements. While the surface has warmed at a rate of ~0.1–0.2 °C/decade for the past 20 years, satellite observations of global temperature show little or no trend over that period (Gaffen *et al.* 2000). As there is a close link between temperature and atmospheric circulation, studying atmospheric circulation can provide valuable clues to the ongoing climate change debate. The observed changes in surface warming have coincided with changes in atmospheric circulation, such as changes in the North Atlantic Oscillation (NAO), the Pacific/North America pattern (PNA), and the Arctic Oscillation (AO) (Hurrell 1996, Thompson and Wallace 1998). The NAO changed into its positive phase around 1980, which has been correlated with wintertime warming observed in surface air temperatures north of 20°N (Hurrell 1996). Changes in the PNA pattern occurred in the mid-1970s such that the Aleutian Low is deepened and shifted eastward, resulting in warm and moist air advection over western North America, and cooler and drier conditions over the central North Pacific. The AO has been significantly trending towards its positive index phase, and the circulation changes associated with these AO trends account for over 50% of the observed warming trend over Eurasia, and 30% of the total Northern Hemisphere (Thompson and Wallace 2000).

Atmospheric circulation has therefore been shown to be a useful indicator of observed temperature trends, and could be a climate change indicator. The circumpolar vortex is used here to address climate change in terms of circulation and temperature. The vortex has been used in a number of studies to quantify hemispheric circulation variability (Angell and Korshover 1977 1978 1985; Angell 1992 1998; Davis and Benkovic 1992 1994; Burnett 1993; Frauenfeld and Davis 2000). It is an effective measure of circulation because it captures multiple aspects of midlatitude circulation variability—the size, shape, strength, and wave pattern—in one variable. It reflects long-wave circulation trends such as changes in standing waves, regional circulation features such as strengthening or weakening of troughs and ridges, and also reflects all non-tropical atmospheric teleconnection patterns and changes thereof. Vortex variability is related to a number of climatological phenomena such as El Niño, the Southern Oscillation, the Quasi-Biennial Oscillation, volcanic eruptions, and the Pacific Climate Shift (Angell 1992 1998; Frauenfeld and Davis 2000). It has been argued that the vortex could be useful in detecting a greenhouse warming signal, with less site biases and urbanization effects than global temperature and precipitation records (Davis and Benkovic 1992; Burnett 1993). The vortex is therefore a potentially useful and effective indicator of surface and tropospheric features, and of climate change and variability.

Atmospheric circulation trends represented by the Northern Hemisphere circumpolar vortex have mainly been investigated through the year 1990. Davis and Benkovic (1992 1994) studied the January 500 hPa vortex for the years 1947–1990, and found an overall expansion of the vortex from 1966–1990, driven by regional expansion over the North Pacific Ocean and eastern North America. Burnett (1993) also investigated size variations in the 1946–1989 January 500 hPa vortex and similarly found a trend towards an expanded vortex after the mid 1960s dominated by changes in the Pacific and eastern North America/Atlantic. The size of the entire 300 hPa circumpolar vortex and quadrants thereof was determined for the period 1963–1989 by Angell (1992), updating the earlier work of Angell and Korshover (1977). Another such update to the 300 hPa vortex trends was performed more recently (Angell 1998), who found that the 1963–1997 300 hPa vortex area was decreasing overall, moreso in the western hemisphere than the eastern.

Only one study (Angell 1998) has investigated the circumpolar vortex with the inclusion of more recent data, but only at one level in the atmosphere. Therefore the implications of the vortex contraction in terms of hemispheric climate change are uncertain. The vortex data set first introduced by Burnett (1993) has recently been updated through the year 2000 and expanded for various levels of the atmosphere. The addition of the last ten years of data can be important for illustrating the Northern Hemisphere vortex response to the recent climate events, such as the prolonged El Niño during the early 1990s, as well as the strong 1997–1998 warm event. More importantly, the inclusion of ten more years of data, to a total of 52 years, provides a considerable increase in the length of the data record for long-term assessments of climate change.

Most of the aforementioned studies only used one geopotential height contour at one level of the atmosphere, and only one month was analyzed over time. Further, while the methodology of Angell (1992 1998) did include all months of the year, the area of the *entire* Northern Hemisphere vortex, and the area of 90° slices of the vortex was analyzed, therefore potentially

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not capturing regional circulation features at scales smaller than 90° of longitude. Although analyzing one geopotential height contour within the core of the westerly flow captures well the overall variability of the circulation's primary baroclinic zone, certain circulation features such as split-flow regimes, as well as geopotential height gradient changes cannot be represented.

Therefore, three contours are used in this investigation, representing the lower, middle, and high latitudes, to determine circulation variability as captured by the Northern Hemisphere circumpolar vortex. Further, 52 years of vortex data for three levels in the atmosphere, 300 hPa, 500 hPa, and 700 hPa, are analyzed here. The important contribution of this research is not only the use of an extended period of record, but also a greatly increased spatial and temporal resolution of the data. To examine climate change impacts on the circumpolar vortex, vortex trends are compared to trends in microwave sounding unit (MSU) satellite temperature records. Vortex size is a reflection of tropospheric temperature (Angell and Korshover 1977) and because the MSU data provide an average atmospheric temperature, Northern Hemisphere MSU trends should be similar to the Northern Hemisphere circumpolar vortex trends. However, at the same time one of the shortcomings of the MSU record in terms of assessing climate change is that it only provides a measure of average vertically-integrated atmospheric temperature, whereas different layers of the atmosphere may exhibit different temperature trends. Therefore, relating the vortex at various levels in the atmosphere to the MSU temperature history is useful for determining how the different layers of the atmosphere behave over time and how strongly they are linked to the MSU record.

2. DATA AND METHODS

The circumpolar vortex data used consist of mean monthly Northern Hemisphere 700 hPa, 500 hPa, and 300 hPa geopotential heights for the period of January 1949 to December 2000 (624 months). The data are derived from the NCEP/NCAR reanalysis data, which consist mainly of rawinsonde data (Kalnay *et al.* 1996). Using this 52-year record of circumpolar vortex data, we selected a mean representative geopotential height contour that consistently falls within the primary baroclinic zone of the 700, 500, and 300 hPa circumpolar vortex for each month of the year. The representative geopotential height was converted into a series of 72 latitudinal and longitudinal intersections along each 5° meridian, so the vortex is represented as a series of 72 straight-line segments connecting the intersections (Burnett 1993). This contour is called the "center contour." To more completely capture the geometry of the vortex, a "southern contour" and a "northern contour" were also selected at each pressure level. These additional contours were chosen to be 2–3 standard contours south and north of the center contour, thereby capturing the circulation of the lower and higher latitudes (Fig. 1). Representative contours and the

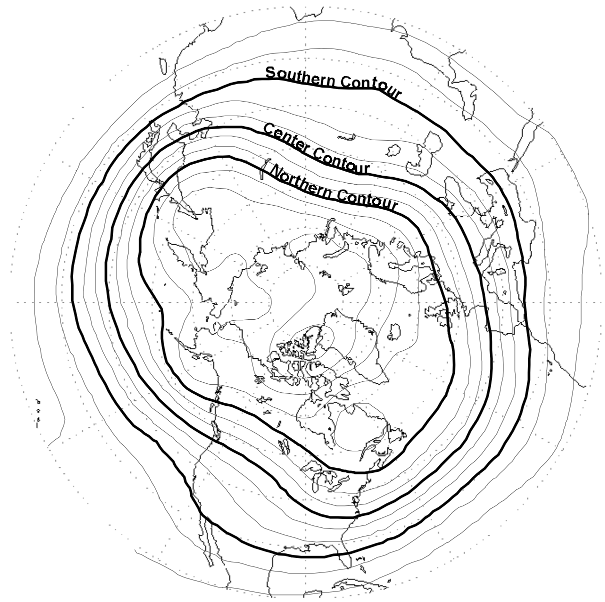

Figure 1. Sample 500 hPa mean monthly geopotential height map depicting the "northern," "center," and "southern" contours for March 2001. Contour spacing is 60 meters.

latitudinal contour positions vary from month to month, and a significant portion of that variability is a function the seasonal cycle in hemispheric temperature gradients. To remove this seasonality, data were standardized with respect to each month's mean and standard deviation.

Least-squares linear regression was used to calculate temporal trends. For the overall vortex, the latitudinal position of each of the 72 standardized vortex slices was averaged across the hemisphere to obtain one mean vortex position for each of the 624 months. A least-squares regression line was then fit to each contour at each level. The time series of the circumpolar vortex exhibit marked non-linear trends, therefore a locally weighted scatter-plot smoothing (LOWESS) curve was also fit to each of the time series (Cleveland 1979). Further, because the Pacific Climate Shift—an abrupt change in temperature that occurred during the winter 1976–1977 (Miller *et al.* 1994)—is very evident in the vortex time series, each time series is divided into the period 1949–1976, and 1977–2000. Independent-samples *t*-tests were then performed between the two periods to establish whether a phase shift is potentially evident in the vortex data set. Least-squares regression was then performed on the two sub-periods to further establish whether the overall trends are the same before and after the potential phase shift, or whether a trend-reversal occurred.

A trend toward overall vortex expansion could arise from large-scale changes across the entire vortex, very strong localized changes (like enhanced troughing), or a combination of the two. To determine the spatial vortex trends for each contour at each level, the slope of the least-squares trend line was determined for the 72 time series representing each 5° longitude-wide vortex sector. These slopes were then plotted to assess where in the Northern Hemisphere the circumpolar vortex is expanding and contracting with time. Again, in order to address the 1976–1977 discontinuity, the spatial trends were also determined for 1949–1976 and 1977–2000.

To reconcile the circumpolar vortex patterns with the Northern Hemisphere temperature history, the MSU 2LT temperature data for the northern hemisphere were used (Spencer and Christy 1993). The MSU is a polar orbiting satellite-borne microwave radiometer that observes the Earth's upwelling radiation, the intensity of which is directly proportional to the temperature of the air. Of the two available MSU records, MSU 2LT was used here because the air temperature calculated from channel 2 (MSU 2) potentially contains a significant cooling signal from the lower stratosphere (NRC 2000). Half of the Northern Hemisphere is comprised of the tropics, and thus 50% of the Northern Hemisphere MSU temperatures would be influenced by the tropical temperature variability. However, the vortex predominantly falls within the 30°N–60°N latitude band. Therefore the 2.5° by 2.5° gridded MSU temperatures were weighted by the cosine of the latitude to account for varying gridbox size, and averaged for the 30°N–60°N band only. Each vortex contour at each level was initially correlated with that MSU temperature time series for the period 1979–2000. Given the notion that the MSU data represent the average atmospheric temperature, a multiple regression model was built using all nine contours as dependent variables, thereby providing a 3 dimensional characterization of the atmospheric circulation. To determine which level of the atmosphere is most closely linked to the MSU 2LT record, multiple regression models were also built separately for each of the three levels.

3. AVERAGE VORTEX TRENDS

The trends of the standardized 624-month time series of the hemispherically averaged vortex show statistically significant overall vortex contraction at every level in the troposphere (Table 1, "Overall" column). At the 300 hPa level, the center contour and the southern contour are significantly contracting, as indicated by the positive trend towards higher latitudes. The southern contour exhibits a stronger contraction than the center contour, while the northern contour's contraction is not statistically significant. In addition to the overall trend toward a more contracted vortex with time, both the time series for the center and southern 300 hPa contours show marked non-linear variability (Figure 2). From the beginning of the record until the mid–late 1970s the vortex was steadily expanding. At the time of the Pacific Climate Shift the vortex shifted from an expanded position back into a near-normal position. For the remainder of the record, the vortex has been contracting and exhibiting much higher-frequency variability than previously; throughout the 1990s the vortex was expanding and contracting on the time-scales of 2–3 years. These same patterns are evident over the last 52 years for all three contours at the 300 hPa level.

To further explore the non-linear nature of the vortex trends and test for impacts of a discontinuity around 1976–1977, a *t*-test was performed between the period before and after the Pacific Climate Shift. The *t*-tests indicate that there is in fact a statistically significantly different mean vortex position before and after the time of the Pacific Climate Shift at each of the three 300 hPa contours (Table 1, "*T*-Test" column). Further, there is a statistically significant vortex expansion in the pre-Shift period and a statistically significant vortex contraction thereafter (Table 1, "Pre/Post Shift" column). These trends are observed for all three of the 300 hPa contours. The pre-Shift expansion is strongest in the southern contour, while the post-Shift contraction is strongest in the northern contour.

Level	Contour	Overall	*T*-Test	Pre/Post Shift
300 hPa	North	0.0534	✔	Pre: **-0.170** Post: **0.102**
	Center	**0.0265**	✔	Pre: **-0.160** Post: **0.080**
	South	**0.0766**	✔	Pre: **-0.190** Post: **0.092**
500 hPa	North	0.0113	✔	Pre: **-0.092** Post: **0.057**
	Center	**0.0438**	✔	Pre: **-0.105** Post: **0.072**
	South	**0.0914**	✔	Pre: **-0.123** Post: **0.074**
700 hPa	North	0.00669	✔	Pre: **-0.078** Post: 0.033
	Center	**0.0499**	✔	Pre: **-0.066** Post: **0.056**
	South	**0.0850**	✔	Pre: **-0.070** Post: 0.044

Table 1. Regression slopes (*z*-score units per decade) for the overall linear trends in the vortex, *t*-tests between the pre- and post-1976–77 Pacific Climate Shift vortex means, and the pre- and post-Shift regression slopes. Bolded values indicate statistical significance at the 0.05 α level, and check marks indicate statistically significantly different means.

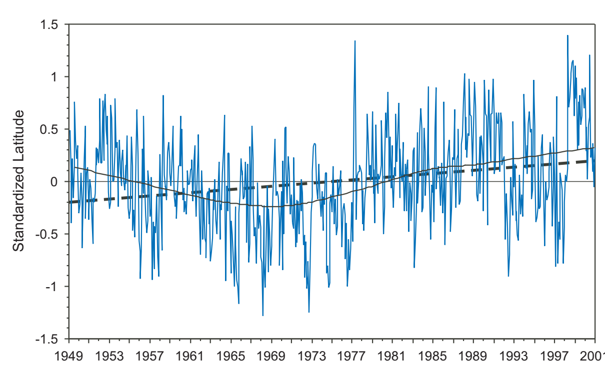

Figure 2. Time series of the 300 hPa southern contour. The dashed line represents the linear least-squares regression line, and the solid curved line represents a locally weighted smoothing curve.

Similar patterns are also observed at 500 hPa and 700 hPa. The overall trend is a statistically significant vortex contraction for both the center and southern contours, and at both levels the contraction is stronger for the southern contour (Table 1). The same non-linear behavior observed at 300 hPa is also evident for each contour at the 500 hPa and 700 hPa levels (not shown). The 1976–1977 Shift also represents a discontinuity as well as a trend reversal at both the 500 and 700 hPa levels. Again, the vortex was expanding until 1976, and contracting from 1977 on. The 1977–2000 contraction trends are not significant for the 700 hPa northern and southern contours.

The overall contraction of the vortex's center contour is strongest at 700 hPa and weakest at 300 hPa, while the southern contour's contraction is strongest at 500 hPa and weakest at 300 hPa (Table 1). Since the vortex is contracting most in the lower latitudes and not at all in the higher latitudes, this also potentially indicates a trend toward an increased meridional height and pressure gradient and stronger westerly flow throughout the Northern Hemisphere troposphere. However, these overall trends seem to be driven by the 1976–1977 discontinuity and are perhaps not indicative of the true vortex trends. The *t*-tests indicate that for each contour at each level, there are statistically significantly different means before versus after the Pacific Climate Shift (Table 1). Further, a trend reversal is also observed around 1976–1977, where the vortex is expanding significantly until the time of the Pacific Climate Shift at each level for each contour and contracting significantly thereafter (Table 1). The post-Shift contraction is strongest at 300 hPa, and stronger at 500 hPa than at 700 hPa, and is not significant for the northern and southern contours at 700 hPa.

4. SPATIAL VORTEX TRENDS

Thus far, the vortex has been treated as a whole by examining the mean hemispheric vortex position only. In the following portion of the analysis, a trend line was fit through the time series of each 5° vortex slice, thus determining the geographic locations where the vortex is expanding and contracting with time. Assessing the spatial trends for the entire time period can potentially result in misleading relationships, since these time series may contain the 1976–1977 Shift as illustrated in the previous section. Therefore, the spatial trends were also determined before and after the Pacific Climate Shift.

It is evident that the overall spatial trends (Fig. 3) are indeed not indicative of the true vortex trends (Fig. 4 and 5). The significant overall trends over Eurasia are actually caused by strong and broad expansion prior to 1976, with only moderate contraction over a narrow region thereafter. The vortex was also expanding significantly over western North America until 1976, and has been contracting in this same region since then. The resulting overall trend only shows moderate contraction. In general, the vortex was expanding over Eurasia and North America prior to the 1976–1977 Climate Shift, and has been contracting in those regions since 1977. The same trends are evident at 500 hPa. At 700 hPa the overall 1949–2000 trends indicate strong contraction from Europe to eastern Asia (Fig. 6). However, the pre- and post-Shift spatial trends indicate virtually no significant areas of expansion or contraction (not shown). This is further evidence that there is indeed a phase shift that occurred in the atmosphere in 1976–1977, and the overall trends are driven by this phase shift.

The spatial analysis indicates that the overall 1949–2000 trends (Table 1) are due to the 1976–1977 discontinuity. The strong expansion prior to 1977, as

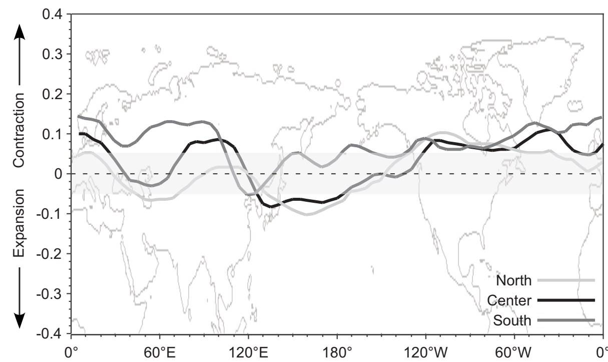

Figure 3. Spatial 300 hPa vortex trends for 1949–2000 in *z*-score units per decade. Trends outside of the shaded box are statistically significant (α=0.05). Basemap is for longitudinal (east-west) reference only.

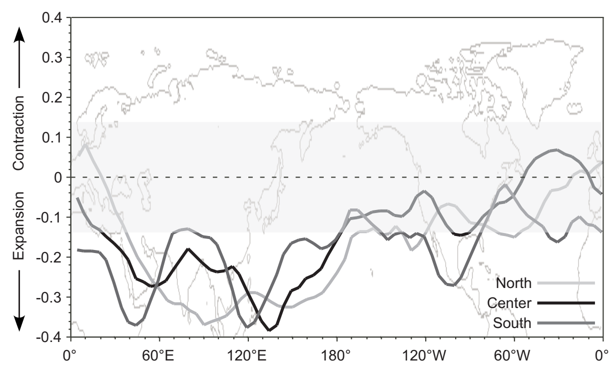

Figure 4. Same as Figure 3, but for 1949–1976.

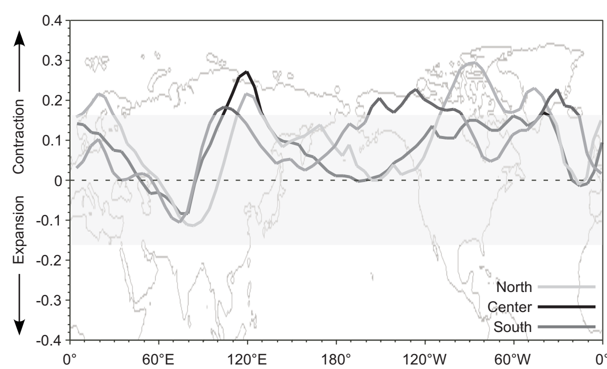

Figure 5. Same as Figure 3, but for 1977–2000.

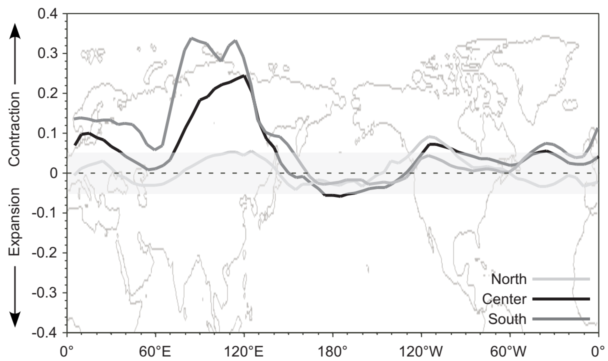

Figure 6. Same as Figure 3, but for 700 hPa.

well as the moderate contraction in the vortex since 1977 from section 3, are driven by expansion and contraction over Eurasia, as well as North America. These patterns of change indicate that there was cooling throughout the atmosphere in those regions before the Climate Shift, and warming thereafter.

5. MSU TEMPERATURE COMPARISON

To reconcile the Northern Hemisphere circumpolar vortex trends with the trends in hemispheric temperature and thus evaluate the degree to which the vortex is sensitive to climate change, the relationship between the midlatitude (30°N–60°N) MSU temperature history and the Northern Hemisphere vortex was established (Table 2). The strongest correlation between the vortex and MSU temperatures is at the 300 hPa level, accounting for 25–50% of the variance (Fig. 7). The correlations between the 500 hPa vortex and MSU temperature are slightly weaker, accounting for 33–38% of the variance. At the 700 hPa level, 16–26% of MSU temperature variability can be accounted for by the circumpolar vortex.

An unexpected finding is that upper rather than lower tropospheric circulation is more strongly related with the MSU 2LT temperature. Since the MSU 2LT data are more heavily weighted by lower tropospheric temperatures, it might be expected to observe the strongest relationships between MSU 2LT and the 700 hPa or 500 hPa vortex. However, the MSU 2LT temperatures are most strongly correlated with the 300 hPa vortex, and more poorly related to the 700 hPa vortex. This suggests that the circulation of the upper troposphere is most responsive to the trends in the MSU temperature, or *vice versa*, and therefore the 300 hPa vortex is most able to capture patterns of climate change and variability.

Calculating a multiple regression model separately for each level in the troposphere, the three 300 hPa contours account for 55% of MSU variability. The three contours at 500 hPa account for 44%, and at the 700 hPa level only the southern contour is significant in the model, and it accounts for 26% of MSU variance. Since the MSU data represent an integrated measure of the temperature of the atmospheric column, a stepwise multiple regression model was calculated using the hemispherically averaged time series of all nine vortex contours. This model accounts for approximately 65% of the variance in midlatitude MSU temperature. Of the nine contours only seven are significant (the three 300 hPa contours, 500 hPa northern and center contour, and the 700 hPa northern and center contour). Almost two thirds of the variability in MSU temperatures can therefore be accounted for by changes in the Northern Hemisphere circumpolar vortex.

Level	Vortex Contour	Midlatitude MSU 2LT
300 hPa	North	**0.504**
	Center	**0.708**
	South	**0.527**
500 hPa	North	0.087
	Center	**0.617**
	South	**0.578**
700 hPa	North	-0.101
	Center	**0.398**
	South	**0.514**

Table 2. Pearson's correlation coefficients for the vortex contours and midlatitude MSU temperature (30°N–60°N); significant coefficients are in bold.

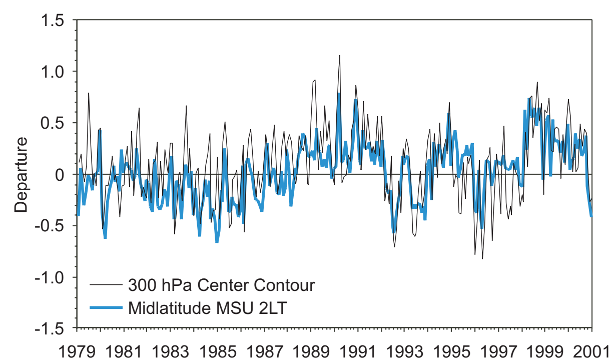

Figure 7. Time series of the 300 hPa center contour and the 30°N–60°N MSU 2LT temperature.

6. SUMMARY AND CONCLUSIONS

With the addition of 10 more years of data to extend previous vortex climatologies, it is evident that the circumpolar vortex is becoming more contracted with time since the 1976–1977 Climate Shift, at every level in the atmosphere. Previous analyses had indicated that the vortex at 500 hPa was expanding over time (Davis and Benkovic 1992), however this trend has changed with the inclusion of the last 10 years of data. Variability over Asia and Europe seems to dominate the overall circulation trends. On average, the vortex is mainly contracting in the upper and middle troposphere and the contraction is strongest in the upper troposphere.

There appears to be a regime shift that occurred in the atmosphere around the time of the Pacific Climate Shift. While the overall vortex trends would suggest that the vortex is contracting with time over the last 52 years, this overall trend is driven by the discontinuity in the Northern Hemisphere circumpolar vortex around 1976–1977. The vortex was expanding until 1976, and has been contracting since then. This pattern is less evident in the lower troposphere, where both the pre- and post-Climate Shift trends are weak, and the post-Shift trends are not significant for the high and low latitudes. The fact that in general the 1949–2000 trends are strongest at 700 hPa, however the pre- and post-trends are weakest, provides further evidence for a regime shift in the Northern Hemisphere circumpolar vortex.

On a regional basis, the vortex was expanding in the upper and middle troposphere over Europe, Asia, and North America until 1976, and has been contracting in those same regions since 1977. No change in atmospheric circulation has been observed over the ocean basins of the Northern Hemisphere, with the exception of the western Pacific. The spatial 1949–2000 vortex contractions are strongest at 700 hPa, however the pre- and post-Shift analysis indicates virtually no change before and after the Climate Shift in the lower troposphere. This again supports the notion that the circumpolar vortex shifted into a different regime at the time of the Pacific Climate Shift.

The fact that the circumpolar vortex is contracting with time since 1977 at 300 hPa, 500 hPa, and 700 hPa has important climate change implications. Following the argument that, hydrostatically, a contracted vortex means that the pressure surfaces are higher and therefore the atmosphere “thicker,” the atmosphere as a whole must also be warming at each of the three layers investigated here. Comparing the vortex trends to the trends in the MSU 2LT temperature history indicates that close to two thirds of the hemispheric temperature variability can be accounted for by the combined vortex variations at all levels. Level by level, the 300 hPa vortex is linked most closely to the hemispheric temperature variability. For a surface warming to have the strongest relationship with the 300 hPa vortex, the warming must be well mixed throughout the atmosphere and not confined to only a shallow surface layer. This could also account for the weaker relationship between MSU 2LT temperature and the 700 hPa vortex. Although the northern contours by themselves are related the least with MSU, all three northern contours are in the stepwise regression model. When considering circulation as a whole, the higher latitudes therefore still contribute significantly to the temperature variability of the Northern Hemisphere. This could be attributable to the fact that atmospheric flow is stronger at the higher latitudes where the atmosphere is more baroclinic, and where the meridional exchange of energy and moisture takes place. However, in the lower latitudes where the atmosphere is more barotropic, circulation is less important and therefore the lower latitudes contribute less to overall circulation variability.

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