Size Variations and Long-Wave Circulation within the January Northern Hemisphere Circumpolar Vortex: 1946–89

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ABSTRACT

The close association between size variations in the Northern Hemisphere circumpolar vortex and surface and middle-tropospheric thermal characteristics makes vortex measurement a valuable tool in monitoring and understanding climate change. Unfortunately, as with most hemispheric circulation indices, measures of total vortex size offer little insight into regional changes in the vortex. Traditional approaches to vortex size calculation, which are based upon planimeter measurements on a polar stereographic projection, limit the ability to examine regional contributions to the total vortex and cannot be used to assess specific linkages between vortex expansion and contraction and the broader class of long wave circulation phenomena. Furthermore, because the scale of the polar stereographic projection varies from one latitude to another, interannual variations in planimeter vortex size measurements are influenced somewhat by the position of the vortex relative to the North Pole.

Many of these problems are avoided if digital data sources are used to calculate vortex size. Digital data enable the calculation of actual earth surface area within longitudinal sectors of the vortex and provide a regional decomposition of total vortex that can be linked with variations in long wave circulation. In this study, digital 500-mb geopotential height data interpolated to a 5° latitude by 5° longitude grid were used to examine size variations in the January circumpolar vortex for the period 1946–89. Total January vortices were smaller than the 44-year average during the period 1946–64, after which larger than average vortices became more common. The last few years of the data record indicate that January vortices may be becoming more contracted again. These patterns of contraction and expansion are not reflective of all sectors of the vortex. Much of the vortex expansion after 1964 occurred in association with amplified troughing over the central Pacific Ocean and eastern North America/Atlantic Ocean. An inverse trend in regional vortex size within the western North American ridge indicates that more frequent occurrences of the positive Pacific/North American teleconnection pattern may be most responsible for the upward trend in total vortex size after 1964.

1. Introduction

During the past two decades, several studies have been published in which the primary research focus was on temporal variations in the size and shape of the Northern Hemisphere circumpolar vortex (Angell and Korshover 1977, 1978, 1985; Markham 1985; Peterlin et al. 1988; Angell 1992; Davis and Benkovik 1992). Many of these studies focused on the relationship between variations in vortex geometry and other meteorological parameters, including surface and middle-tropospheric temperature, Southern Oscillation, quasi-biennial oscillation, and sunspot activity. The search for such relationships is not surprising and is not without cause given the close association between hemispheric energy dynamics and the size, shape, and strength of the circumpolar vortex. For example, vortex size and strength exhibit strong seasonal fluctuations, which are characterized by vortex enlargement and strengthening during the winter, and by vortex contraction and weakening during the summer. In addition, vortex shape, which is influenced largely by long waves embedded within the vortex, exhibits seasonal fluctuations that are a response to changing surface thermal contrasts. However, superimposed upon these seasonal characteristics are year-to-year changes in vortex geometry that are indicative of climate variation over longer time scales. Unfortunately, the bundled interaction between the circumpolar vortex and the dynamic factors that influence it make the determination of cause and effect relationships difficult; however, as Angell (1992) explains, vortex measurement provides an integrated view of the middle-latitude climate system and is a valuable tool in monitoring and understanding climate change.

As with most hemispheric circulation indices, circumpolar vortex measurements suffer from the inability to provide regional generalizations of the impact of localized circulation changes on the overall index. A single measure of total vortex size (to be defined) may not be reflective of size variations within all regions of the vortex. If total vortex size expands, does this imply that all parts of the vortex have expanded? Vortex expansion or contraction may be limited to a few re-

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gions, such as within a long-wave trough or ridge. In such cases, expansion or contraction of the vortex may be related to changes in wave amplitude. Other authors have expressed interest in long wave amplitude variation, particularly as it pertains to changes in airmass advective patterns and temperature at the earth's surface (Kalnicky 1974; Bryson 1975; Diaz and Quayle 1980; Knox et al. 1988; Leathers et al. 1991). Many authors have reported that long-wave circulation was more zonal during the 1940s and 1950s, after which the flow became more meridional. Yarnal and Leathers (1988) and Shabbar et al. (1990) found this result to be reflected by the Pacific/North American teleconnection pattern. A more regionalized look at the circumpolar vortex size and its relationship with long wave circulation patterns could be used to refine and expand upon these findings.

Unfortunately, most of the earlier circumpolar vortex climatologies were performed using data recorded after 1963 only, and do not capture changes in vortex size during the period when changes in wave amplitude were reported, nor do these studies focus on regional changes in vortex size to the extent that individual wave features can be resolved. Furthermore, traditional approaches to vortex measurement have created inconsistencies among the resultant climatologies. The method by which the vortex size is measured typically involves the use of a planimeter to measure the area contained within a representative circumpolar geopotential height contour on a 500- or 300-mb polar stereographic projection. Representative contour selection is usually subjective and depends upon the objectives of the researcher. Markham (1985), in his analysis of 500-mb vortex size as a measure of surface temperature, used a common contour for all months in order to capture the seasonal expansion and contraction of the vortex. By contrast, Angell and Korshover (1977, 1978, 1985), Peterlin et al. (1988), and Angell (1992) varied the representative vortex contour depending upon season in order to stay close to the core of the main belt of the westerlies. Such differences in contour selection make it difficult to compare vortex climatologies.

Another problem that is common to most vortex climatologies involves the use of the polar stereographic projection as the primary data source. Because the scale of this projection varies from one latitude to another, year-to-year differences in planimetered vortex area are dependent partially on the position of the vortex relative to the North Pole. Consequently, the relationship between planimetered vortex size and the actual earth surface area contained within the vortex is not consistent. Angell and Korshover (1977) recognized this problem and proposed a correction factor that was based upon the latitudinal displacement of the vortex center from the North Pole.

Many of these problems can be avoided by calculating vortex area directly from digital geopotential height grids, rather than from polar stereographic plots. Digital data sources provide much more flexibility in representative contour selection and vortex area calculation. The representative contour need not be restricted to that set of heights shown on the polar stereographic plot, but rather can be any height that is thought to best represent the core of maximum circumpolar flow. Once the representative pressure height is identified and the latitude and longitude intersections of the contour located, the actual earth surface area of that region north of the representative height can be determined. This procedure avoids the scale change problems that are associated with area measurements directly from polar stereographic projections. In addition, a digital vortex measurement scheme enables the calculation of area within small sectors of the vortex, making it easier to examine regional contributions to total vortex expansion and contraction. Regional assessments of vortex size using planimeter measurements, such as that performed by Angell (1992) for the quadrants 0°–90°W, 90°W–180°, 0°–90°E, and 90°E–180° offer some impression of the regional structure of the vortex. However, this approach is time consuming and limits the ability to capture vortex size variations at scales necessary to resolve individual long wave features.

The value of circumpolar vortex size measurement as a bundled circulation index in which many characteristics of middle-latitude flow are integrated makes it a useful tool in climate change assessment. However, methodological concerns associated with traditional vortex measurement schemes and the lack of a detailed examination of regional contributions to vortex size limit the application of this index. This analysis seeks to address these issues and expand upon earlier vortex studies through the following research objectives:

1) To develop a vortex size measurement scheme that uses digital data sources, thereby providing more flexibility in vortex measurement. This flexibility should enable a better assessment of the representative geopotential height, eliminate the need to manually measure vortex size on polar stereographic plots, and simplify the regional decomposition of the total vortex size.

2) To use this new scheme to construct a temporal vortex size climatology for January months spanning the years 1946–89. Other authors have noted that patterns of middle-tropospheric circulation variability are most clearly defined during the winter months, when hemispheric thermal gradients are strongest (Balling and Lawson 1982; Reiter and Westhoff 1982; Shabbar et al. 1990). Although considerable intraseasonal flow variation can exist among winter months, January data should provide a representative sample of the winter vortex climatology.

3) To determine whether variations in the total vortex size are reflective of vortex expansion or con-

traction throughout all parts of the vortex. Perhaps the trend in total vortex size is a function of expansion or contraction in certain geographic regions. Can this issue be linked to variations in long wave amplitude?

2. Data and approach

The data for this study consist of mean January Northern Hemisphere 500-mb geopotential heights for the period 1946–89. These data were derived from NMC operational daily analyses on a 1977-point octagonal grid with a horizontal resolution of 380 km (Jenne 1975). Some authors have commented on the reliability of these data for the examination of middle-tropospheric climate change (Haines and Winston 1963; Wahl 1972; Parker 1980; Reiter and Westhoff 1982; Carleton 1988; Knox et al. 1988; Lambert 1990; Shabbar et al. 1990; Leathers and Palecki 1992). Many of these authors have expressed concern that changes in data sources and analysis procedures may have introduced discontinuities in the resultant dataset that might be mistaken for climate change. However, some argue that collateral changes in other datasets, like surface temperature, show variations that are consistent with those observed in the middle-tropospheric datasets (Leathers and Palecki 1992). Discontinuities in the middle-tropospheric gridded data record that are caused by changes in data source or analysis should not be apparent in other datasets unless they are signals of actual climate variation. Notwithstanding these issues, the NMC operational analyses comprise one of the most spatially and temporally comprehensive middle-tropospheric data records available and should provide a reasonable assessment of circumpolar vortex size variation for this study.

The process of selecting a representative pressure height or contour was based on the assumption that the vortex is best defined by that region of strongest meridional height gradient. In order to meet this criterion, each January octagonal grid was first interpolated to a 5° × 5° latitude and longitude grid extending from 25°N to 85°N latitude. Geopotential height changes were then examined along each 5° meridian for each January data grid to determine the average height within the 5° latitudinal zone of greatest height change. These values were then averaged for all January months, thereby producing a single 500-mb geopotential height that best defines the January circumpolar vortex.

The representative geopotential height was encoded for each January data grid as a series of latitudinal and longitudinal intersections along each 5° meridian, thus depicting the vortex as a series of straight line segments connecting these intersections. The earth surface area contained within each of these 5° segments was defined as a sector bounded north by the North Pole, south by the average latitude of the segment, and east and west by the longitudes of the sector sides. This procedure is demonstrated graphically in Fig. 1 for a simplified vortex and is described in more detail in the accompanying Appendix. The total vortex size was calculated by summing the areas of all the smaller 5° longitude sectors.

3. Results and discussion

A plot of the total January vortex area departures for a representative geopotential height of 5454 meters is shown in Fig. 2 and reveals a temporal trend that is characterized by smaller than average vortices during the earlier part of the record and larger vortices in the later part of the record. The last few years of the record suggest that January vortex size may be becoming more contracted again. This trend is highlighted by a locally weighted smoothing curve, which shows a tendency toward larger than average vortices beginning in 1965 and a slight decrease in vortex size after the middle 1980s. One reviewer pointed out that an examination of January-mean 500-mb charts for 1990–92 supports a continued pattern of contracted vortices, with lower than average vortices in 1990 and 1991, and a near-normal vortex in 1992. A tendency toward smaller vortices after the middle 1980s is consistent with the increases in 850–300-mb temperatures over the middle latitudes that were reported by Angell (1988, 1992). However, the relationship between vortex size, as measured by a single geopotential height contour, and

FIG. 1. A simplified representation of the circumpolar vortex area measurement scheme. The vortex (shown here by the heavy black line) is represented by a series of latitude and longitude intersections that are used to define the element bounded north and south by the North Pole (ϕ_1) and the average colatitude of the vortex sector (ϕ_2), and west and east by the longitude intersections of the sector (θ_1 and θ_2).

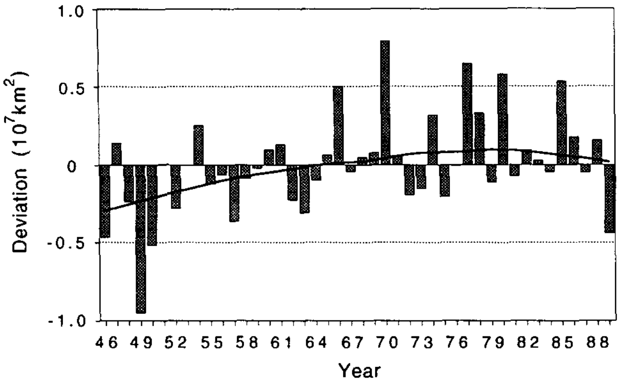

FIG. 2. Total January vortex area during the period 1946–89. Values are shown as departures from the 44-year average January total vortex area. A locally weighted smoothing curve is superimposed on the data series to highlight the trend toward larger vortices after the mid-1960s.

middle-tropospheric temperatures and geopotential heights over the middle and high latitudes can be complicated by the influence of highly meridional flow. For example, during extended periods of blocking, the presence of considerable north/south circulation structure may contribute to an unusually large vortex measurement. In such cases, an expanded vortex need not be always associated with a deep, cold polar vortex (Angell 1992).

The significance of vortex size increases after 1965 was examined with an iterative *t* statistic using varying two-group combinations (Knox et al. 1988). By varying the number of contiguous years contained within the first and second group, those groups that exhibited the most significant difference in mean vortex size could be identified. As expected, this break occurs between the 1946–64 group and the 1965–89 group. This finding can be linked with the results presented by Knox et al. (1988), who showed that 500-mb geopotential heights averaged for the Northern Hemisphere over 30°N–80°N were higher than average during the period 1946–62 and lower thereafter. Such a finding is consistent with a contracted circumpolar vortex during the 1946–62 period.

A comparison of the total vortex area results shown in Fig. 2 and those presented by Angell (1992) for winter 300-mb planimeter vortex measurements since 1963 shows modest agreement. In both cases, circumpolar vortices exhibit maximum expansion in the late 1970s and a tendency toward contracted vortices in the late 1980s. However, noticeable differences do exist between the datasets. The data presented in Fig. 2 do not exhibit as much vortex contraction in the 1980s as does Angell's (1992) data. These inconsistencies may be related to the different approaches by which vortex areas were calculated. The use of January-mean data as representative of winter circulation in this study may also contribute to some difference.

As with many hemispherically derived circulation indices, total vortex size offers little insight into regional variations in vortex geometry. Although these results support a trend toward larger total circumpolar vortices after 1964, this conclusion does not indicate whether this expansion is characteristic of all parts of the vortex. This question was addressed through an examination of the statistical association between the 44-year time series of total vortex area and the area time series of each of the individual 5° longitude vortex sectors. Those sectors that expand and contract in unison with the total vortex series should exhibit strong positive correlations, whereas those areas that are not strongly associated or inversely associated with the total vortex trend should be weakly or negatively correlated.

Figure 3 displays a plot of these associations and supports the hypothesis that trends toward larger total vortex size after 1964 are not reflected in all regions of the vortex. The highest positive correlations are limited to two regions over the central Pacific Ocean and eastern North America/Atlantic Ocean. Although not statistically significant at the 0.05 probability level, the region over western North America does associate negatively with the overall vortex size series and is suggestive of an inverse trend to that shown by the total vortex size.

When this regionalization is compared to the overall 500-mb geopotential pressure height change between the pre-1964 period, when total vortices were smaller, and the post-1965 period, when vortices were larger, those regions that exhibit strong positive associations with this general trend are located near areas of large height fall (Fig. 4). Furthermore, these regions also correspond primarily with major mean trough locations in the expanded vortex. This relationship is shown by the shape of the mean 5454 geopotential meter contour for the 1965–89 period, which is plotted on Fig. 4 as well. Vortex expansion within these troughing regions is indicative of wave amplification. As expected with wave teleconnection, height decreases in these

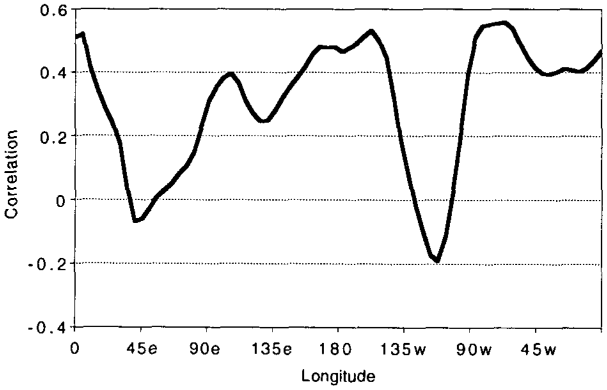

FIG. 3. Correlation between the 44-year series of total January vortex areas and the 44-year series of surface elements defined by each of the individual 5° longitude vortex sectors.

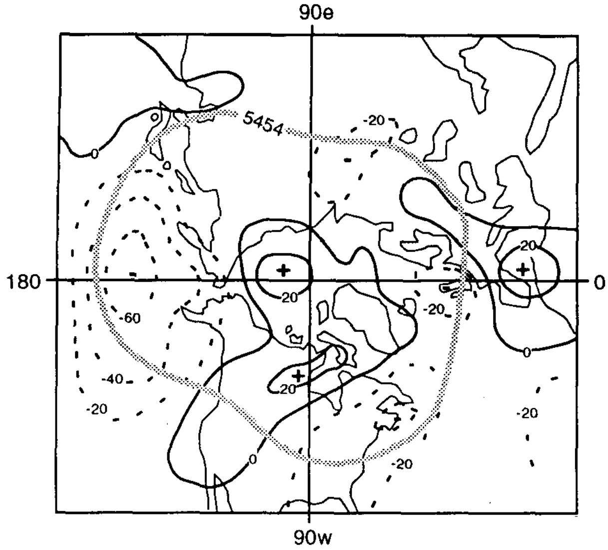

FIG. 4. January 500-mb geopotential height change between the 1946–64 period, when vortices were smaller than average, and the 1965–89 period, which is characterized by larger than average vortices. The heavy line shows the location of the January circumpolar vortex representative geopotential height (5454 meters) for the 1965–89 period.

troughs should be associated with increases in heights in the intervening ridge and an inverse vortex size association. This hypothesis is supported by the negative correlations over western North America, which is a region characterized by broad ridging. Vortex expansion over the central Pacific and eastern North America/Atlantic Ocean and weak vortex contraction over western North America after 1964 is characteristic of an enhanced positive Pacific/North American flow regime, similar to that trend shown by Yarnal and Leathers (1988) and Shabbar et al. (1990). These results suggest that amplification within this teleconnection pattern is most responsible for the larger than average vortices after 1964.

4. Summary and conclusions

Measures of circumpolar vortex geometry have long been used as indices of middle-latitude circulation and have been shown to be closely linked with other meteorological parameters. However, the full utility of such indices is realized only when such relationships can be linked with regional variations in circulation and ultimately associated with the processes by which these variations are driven. This study moves the issue of circumpolar vortex climatology in this direction by offering a more flexible approach to vortex measurement that uses digital data rather than traditional map data sources. Although the selection of a single representative geopotential height will always be questioned in its ability to adequately describe the location of the vortex, digital data sources provide a vehicle by which different, and potentially multiple, criteria can be used to represent the vortex. The use of digital data in vortex measurement enables the calculation of vortex area in terms of actual earth surface, thus avoiding the scale change problems that are associated with polar stereographic maps. Furthermore, this technique offers a regional evaluation of vortex size that can be used to examine variations in long wave circulation and provides findings that are consistent with those of previous climatologies. In particular, the results of this analysis show:

1) January circumpolar vortices as defined by the earth surface area poleward of the 5454-geopotential meter contour, were contracted during the late 1940s, the 1950s, and the early 1960s relative to the 44-year average. Circumpolar vortices were generally larger between 1965 and the mid-1980s. Since then, the trend in vortex size has been slightly downward. More frequent episodes of expanded circumpolar vortices after the mid-1960s may be linked with the reduction in average 500-mb geopotential heights for the Northern Hemisphere (30°N–80°N) found by Knox et al. (1988) for the period 1963–85 compared with 1946–62.

2) Not all regions within the vortex followed this trend of contraction and expansion. Much of the vortex expansion after 1964 occurred in association with amplified troughing over the central Pacific and eastern North America/Atlantic regions. Weakly negative associations within the intervening western North American ridge suggest a linkage with more frequent episodes of positive Pacific/North American circulation after the mid-1960s, similar to that described by Yarnal and Leathers (1988).

This approach to circumpolar vortex study combines the quality and utility of a hemispheric circulation index with the ability to decompose and examine vortex size variations on a regional scale. This flexibility provides a vehicle by which climate change can be monitored and the regional nature of this change assessed, both of which are important in light of the growing concern involving anthropogenic influences on the climate system. The integrated relationship between the circumpolar vortex and hemispheric energy dynamics bind vortex behavior with variations in the hemispheric energy budget. Consequently, changes in the energy budget, such as might occur in association with a continued increase in the concentration of atmospheric greenhouse gases, should be reflected by changes in vortex geometry. However, circumpolar vortex analysis achieves broader significance with the ability to regionalize these changes. In this fashion, vortex expansion and contraction can be linked to a wider range of circulation phenomena, such as long wave teleconnective patterns. Ultimately, such a regionalization serves to isolate and illuminate the underlying causal factors that drive variability in these phenomena.

APPENDIX

Calculating the Circumpolar Vortex Area

The area of a surface element, $d\phi$ and $d\theta$, on a sphere of unit radius is the product of the change in colatitude $d\phi$ and of longitude $d\theta$. The latter is also a function of ϕ. In Fig. 5, an element of the spherical surface is defined by a change in colatitude $d\phi$ and a change in longitude $d\theta$. The side of the surface area that is contributed by the changing colatitude is:

$$\rho d\phi \tag{A.1}$$

where ρ is the earth's radius. The side of the surface element that is contributed by changes in longitude is evaluated relative to the x–y plane through the element and is

$$\rho \sin\phi d\theta. \tag{A.2}$$

Therefore, the surface area of the small element is

$$\rho^2 \sin\phi d\phi d\theta, \tag{A.3}$$

and the area of a regional sector with boundaries (ϕ_1 and ϕ_2) and (θ_1 and θ_2) is

$$\rho^2 \int_{\theta_1}^{\theta_2} \int_{\phi_1}^{\phi_2} \sin\phi d\phi d\theta. \tag{A.4}$$

In this paper, ϕ_1 at the North Pole is zero, and the expression reduces to

$$\rho^2 (1 - \cos\phi_2)(\theta_2 - \theta_1). \tag{A.5}$$

The area of the circumpolar vortex is the sum of 72 5° longitude contiguous regional sectors.

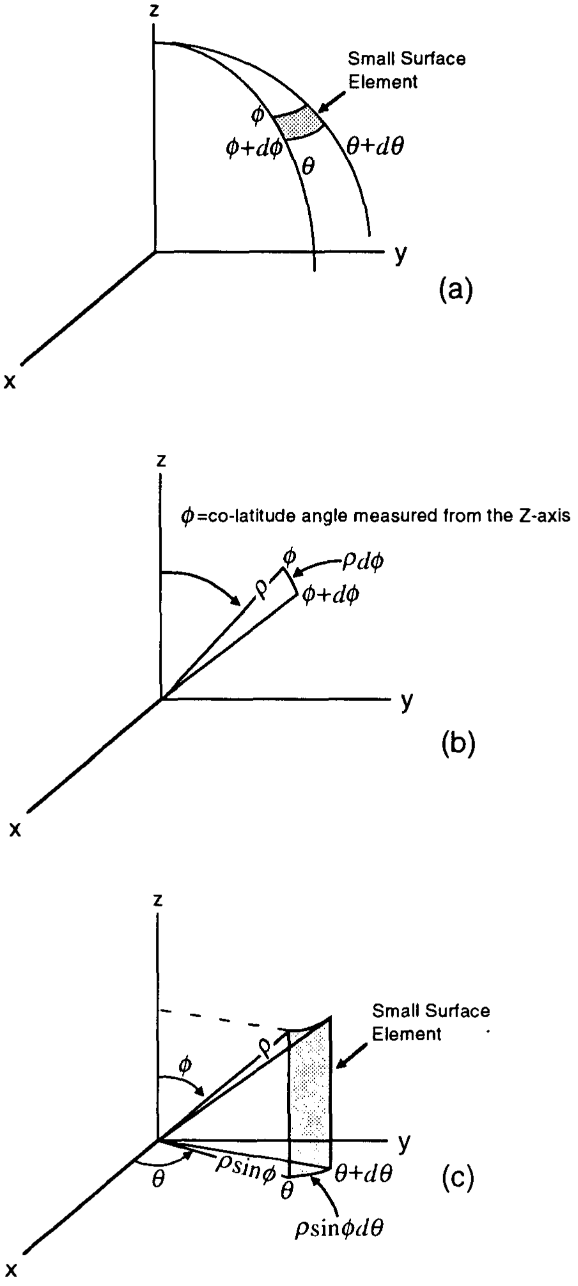

FIG. 5. (a) Small spherical surface element bounded north and south by ϕ and $\phi + d\phi$, and west and east by θ and $\theta + d\theta$. (b) Length of the north/south arc of the surface element. (c) Length of the west/east arc of the surface element.

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