Meteorol Atmos Phys 96, 21–28 (2007)
DOI 10.1007/s00703-006-0218-3
Printed in The Netherlands

Meteorology and Atmospheric Physics

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Decay of the Northern Hemisphere stratospheric polar vortex and the occurrence of cut-off low systems: An exploratory study

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With 2 Figures

Received March 7, 2006; revised April 5, 2006; accepted June 12, 2006
Published online: December 20, 2006

Summary

The authors perform an exploratory analysis on the effect of the timing of the stratospheric vortex breakup in the occurrence of cut-off low systems (COLs) in the Northern Hemisphere. The first multidecadal Northern Hemisphere COLs database (Nieto et al, 2005) covering a 41 year-long period (1958–1998) was used in the analysis. The dates of stratospheric vortex breakup were obtained using two different approaches recently purposed in literature based in potential vorticity and zonal winds. An analysis of differences of COLs occurrences for the five earlier (later) breakup years showed that, at latitudes lower than 45° N, COLs are more frequent for earlier vortex years during the following spring and summer. The monthly analysis showed that, in general, the significant differences start in May lasting until September, being especially relevant for the European sector, the area with the highest rates of COLs occurrence in the Northern Hemisphere.

1. Introduction

The most distinctive feature of the circulation of the winter stratosphere is a large cyclonic vortex centered close to the winter pole (Haynes, 2005). The strong circumpolar westerly circulation associated to the vortex isolates the air inside the vortex, reducing mass exchanges with the exterior. Potential vorticity provides what is arguably the best large-scale field to characterize this isolation. The stratospheric vortex is a region of high potential vorticity (PV), with the location of wind maximum values coinciding with the region of steep PV gradients at the edge of the vortex. In recent years there has been a considerable interest in studying several characteristics of the vortex, such as its inner mean temperature, its area, its shape or its intensity. This increase of interest arises because the Polar vortex impact in the concentration of stratospheric ozone or its modulation role in the dynamical stratosphere-troposphere coupling (Knudsen and Andersen, 2001; Newman et al, 2001). Two complete climatologies of stratospheric vortices have been developed recently based on NCEP/NCAR (Waugh and Randel, 1999) and ECMWF (Kapetchko et al, 2005, hereafter K05) reanalysis. One of the main results of these previous studies is that the Arctic vortex (location, area or strength) is highly variable throughout its life cycle, but particularly during the spring vortex breakdown. The timing of the breakup of the NH wintertime polar vortex in the lower stratosphere (vortex decay) has important chemical and dynamical implications (Waugh and Rong, 2002). Furthermore, taking into account that the vortex decay is associated with the winter to summer transition, the precise timing of these events has implications in the hydrological cycle (Cayan et al, 2001) and in the weather conditions (Wang and Key, 2003). In general, there is reduced ozone concentration during years with a late breakup (Knudsen et al, 1998), because of reduced transport of ozone-rich air into the polar lower stratosphere.

Dynamically, results found by Black et al (2006), (hereafter B06) are especially important. They have found that the vortex breakup sharpens the annual weakening of the circumpolar westerlies in both the stratosphere and troposphere associated with a large-scale dynamical coupling of the stratosphere and the troposphere. The weakening of the westerlies at tropospheric levels is so intense after the vortex decay that triggers a quasi-steady summerlike state afterwards. These results would be especially interesting if the trend to more persistent vortices found during the 90s against the 80s were confirmed, due to the fact that a longer-lasting vortex is associated with a colder polar stratosphere that results in stronger ozone losing, affecting also stratospheric dynamics (Zhou et al, 2000). However the recent study by K05 shows that there is no significant trend in the vortex longevity in the period 1975–2002, due mainly to the very early breakup in the winter of 2000/2001. Other important dynamical aspect concerning the decay of the vortex is the persistence of coherent potential vorticity structures after the breakup. Waugh and Rong (2002) showed that in early breakup years (vortex decay in early March) the remnants of the vortex survive as coherent potential vorticity structures for around two months, whereas in late breakup years (vortex decay in late April or May) the potential vorticity remnants quickly dissipate.

Among the most representative coherent potential vorticity structures are the cut-off low systems (COLs), which can be considered as isolated regions of high potential vorticity that affect both the stratosphere and the troposphere. In terms of atmospheric pressure, COLs are synoptic-scale-low pressure systems formed as a result of meridional shifts of jet streams (Palmén and Newton, 1969; Winkler et al, 2005) at upper troposphere (around 200 hPa). These systems present a closed circulation on upper-air isobaric maps and play a significant role in most exchange processes between troposphere and stratosphere (Holton et al, 1995), particularly in the ozone-exchange (Kentarchos et al, 2000). The COLs implications in the weather, mainly referred to convective precipitation and flash floods are also well-known (e.g., Porcù et al, 2003; Tripoli et al, 2005). According to the recent comprehensive climatology of COLs (Nieto et al, 2005) there are two relevant results to this study, (1) COLs are much more frequent during summer than during winter and, (2) there are three recognized preferred areas of COL occurrence: Southern Europe and Eastern Atlantic coast (European sector), the Eastern North Pacific (Pacific sector), and the Northern China and Siberian region including to the Northwestern Pacific coast (Asian sector), being the European sector where the occurrence is the highest.

There are two dynamical reasons to think that COLs occurrence could be influenced by the persistence of the stratospheric vortex, (a) the quasi-steady summerlike state after the vortex decay with strong weakening of the westerlies favors COL development, and (b) the fact that remnants of the vortex survive as coherent potential vorticity structures for around two months for early breakup years. These two arguments suggest that COLs should be more frequent during late spring and summer months for those years when the vortex decays earlier. The main objective of this paper is to evaluate the plausibility of this hypothesis.

2. Data and method

2.1 Persistence of the Arctic vortex

There are two main modes of diagnostics of the stratospheric vortex breakup, one based in potential vorticity and the other based in zonal winds. Although there are several ways to estimate breakup timing from potential vorticity, the most common is that developed by Nash et al (1996). They defined first the vortex edge as the location of maximum PV gradients constrained by the location of maximum wind speed calculated around the PV isolines, and then the breakup date is defined as the date when the maximum wind speed along the PV isolines falls below a critical value. When using zonal winds the standard approach is based on computing the zonal-mean zonal wind at a pressure level (typically from 10 to 50 hPa) and at a latitude close to the core of the stratospheric vortex (typically 70° N). Then the breakup date is defined as the date when the averaged zonal winds drops to zero without returning to a specified threshold value until the subsequent fall. We have used data of vortex breakup for the period 1958–1998 from two studies, one using potential vorticity analysis (K05) and the other using average zonal winds (B06). K05 calculated breakups at several isentropic levels from ECMWF reanalysis and the vortex breakup date was defined as the date when the maximum wind speed (averaged around the vortex edge) drops below 15.2 m/s. B06 used NCAR-NCEP reanalysis and identified the breakup date as the final time that the zonal-mean zonal wind at 70° N and 50 hPa drops below zero without returning to positive values until the following fall.

2.2 COLs occurrence

The daily multidecadal dataset from Nieto et al (2005) was used. The COL dataset was constructed by using 41 years (1958–1998) of NCEP-NCAR daily reanalysis data at 200 hPa and 300 hPa levels (geopotential height, zonal wind, and temperature) with a 2.5° by 2.5° resolution. This analysis is based on an identification of COLs by means of three consecutive steps based on physical characteristics of the conceptual model of COLs (Winkler et al, 2005) for the extratropical Northern Hemisphere in a band from 20° N to 70° N. These three steps are: (a) Geopotential minimum and cut-off circulation at 200 hPa. In this step, two characteristics of COLs were considered, the condition of a minimum of geopotential field at 200 hPa and the isolation of the system from the westerlies general circulation in the upper troposphere. (b) Equivalent thickness. In a COL, this field is characterized by a thickness ridge in front of the low. The pressure levels chosen to calculate this field were 200 and 300 hPa. (c) Thermal front parameter (TFP). TFP is the change of temperature gradient, at the 200 hPa level, in the direction of the temperature gradient. One of the two baroclinic zones in a COL is placed in front of the low, which is connected with a frontal-like cloud band. So, the grid point eastward of the COL representative point must have TFP values higher than this COL point to continue considering the system as a COL. For all the steps they have also required the following rules to consider that the points of COL were from a same COL: the grid points belonged to the same COL when these points were adjacent and it was considered that a COL was the same in two consecutive days when any of the grid points that fitted the COL condition had, in the following day, at least one contiguous grid point fitting the condition. When several adjacent points fitted these criteria on the same day, the northernmost and westernmost grid point was used as the representative position of the COL. This choice permits to identify the closest point to the general circulation where the circulation is cut-off.

2.3 Determination of earlier and later breakup years

The five years with lower and higher persistence were used to evaluate the contrast in timing of COLs occurrence. This was done using four different series of breakup dates, called hereafter B06, K05-475, K05-600 and K05-875, where the number after K05 refers to the used isentropic level (475, 600 and 875 span the stratosphere from about 80 to 10 hPa). Previous studies (Waugh and Randel, 1999) concluded that different methods to estimate breakup dates give very similar results, being the variability in the timing of the breakup qualitatively the same. However there could be important differences due to the different height chosen to characterize the vortex and the different threshold chosen in the wind intensity to define the breakup. The breakup typically takes a week to progress from the mid to the lower stratosphere, so it is expected that the breakup occurs earlier at 875 K than at 475 K. As K05 uses critical wind speed of about 15 m/s and B06 of 0 m/s, it is expected that the breakup occurs earlier using K05 series than using B06. This last difference could be very important for the breakup dates of individual years. If during that year wind speed drops below 15.2 m/s without reaching negative values during the following weeks, then the difference in the breakup dates between B06 and K05 could be important. As we used in our analysis five extreme years in vortex persistence, the inclusion of any of these non-concordant years could influence on the results. Table 1 shows the five earlier and later breakup years for the four series used and their thresholds

Table 1. Five earlier (later) breakups years according to Karpetchko et al, 2005 (K05), Black et al, 2006 (B06) and the combined criterion. Numbers after K05 refer to the used isentropic level (in K). Thresholds refer to the maximum date for earlier breakup years and the minimum for later ones. Italic numbers after the year in combined B06-K05 refer to breakup dates for that year according to B06, K05-475, K05-600 and K05-875, respectively

	Five earlier breakup years	Five later breakup years	Thresholds
B06	1984, 1971, 1961, 1975, 1983	1973, 1981, 1990, 1967, 1987	80/118
K05-475	1958, 1987, 1989, 1984, 1973	1997, 1990, 1967, 1962, 1968	81/117
K05-600	1958, 1987, 1989, 1984, 1973	1997, 1965, 1990, 1962, 1967	84/120
K05-875	1989, 1991, 1973, 1984, 1959	1962, 1965, 1960, 1997, 1970	83/116
Combined B06-K05	1984 (*73, 79, 76, 81*)	1990 (*133, 130, 121, 112*)	94/111
	1971 (*75, 90, 88, 84*)	1967 (*128, 121, 120, 112*)	
	1961 (*78, 94, 91, 88*)	1962 (*126, 119, 121, 130*)	
	1975 (*79, 88, 89, 86*)	1968 (*124, 117, 114, 111*)	
	1964 (*83, 92, 91, 90*)	1997 (*123, 130, 130, 120*)	

expressed in breakup dates. A good agreement happens in most of the years (e.g., 1984) but there is a clear example of non-concordant year (1973) that is considered as an earlier breakup year using K05-475 and K05-600 but as a later year using B06. So, in order to guarantee consistent early and late breakups, we opted to use the five years by group with best agreement among the different series to contrast COL occurrence. This choice was labeled "combined B06-K05" (Table 1) and uses breakup date thresholds of 94 and 111 days, slightly less restrictive than using the original series, but safer and more appropriate for our analysis. 1964 and 1989 are good examples to illustrate the combined choice. The first one is not one of the five early vortex breakup years in any of the four individual sets of breakup dates while the second one is included in three of the four sets. However, the highest date of breakup for the four sets during 1964 was 92 whereas during 1989 the highest date was 104 (for B06 set, not shown in Table 1).

3. Results

We first examine the differences in the total number of COLs respect to shorter and longer vortex persistence. Table 2 shows the number of COLs for the ten extreme years included in the analysis (N) and for the five later and five earlier breakup years according to the B06-K05 criterion. The computation was done for the whole Northern Hemisphere between 20° N and 70° N –the area studied by Nieto et al (2005)–, for latitudes lower (and higher) than 45° N, and for the three sectors of higher COLs occurrence found by Nieto et al

Table 2. Number of COLs for the ten analyzed extreme years (N) and for the five later (earlier) breakup years (in brackets, percentages). The Northern Hemisphere from 20° N to 70° N and the three sectors correspond to the whole analyzed area and the main sectors of COLs occurrence in Nieto et al (2005)

	N	Five later breakup years	Five earlier breakup years
Northern Hemisphere 20° N–70° N	560	274 (48.9%)	286 (51.1%)
Northern Hemisphere 20° N–45° N	338	157 (46.4%)	181 (53.6%)
Northern Hemisphere 45° N–70° N	222	117 (52.7%)	105 (47.3%)
European sector 25° N–47.5° N, 50° W–40° E	151	64 (42.4%)	87 (57.6%)
Pacific sector 25° N–45° N, 100° W–150° W	65	30 (46.2%)	35 (53.8%)
Asian sector 35.7° N–62.5° N, 100° E–180° E	81	43 (53.1%)	38 (46.9%)

(2005): the European sector (25° N–47.5° N, 50° W–40° E), the Pacific sector (25° N–45° N, 100° W–150° W) and the Asian sector (35.7° N–62.5° N, 100° E–180° E). With the single exception of the European sector –the area with the higher occurrence of COLs in the Northern Hemisphere–, COLs occurrence was similar when the vortex decays earlier than when it decays later. In the European sector this difference in the COL occurrence according to the persistence of the vortex was clear (87 COLs during the five earlier breakup year's vs 64 during the five later ones). However the lack of discrepancy in the annual COL occurrence in earlier/later vortex breakup years does not refuse our hypothesis.

According to the two dynamical reasons commented in the introduction, this difference should become apparent mainly during spring and probably during summer. Furthermore, the different persistence of the vortex could affect in a different way to COLs occurring at lower/higher latitudes, because of the different nature of the jet streak which led to their formation (Price and Vaughan, 1992). So, we have studied the seasonal and monthly occurrence frequencies of COLs for earlier and later breakup years and for two latitudinal bands, from 20° N to 45° N and from 45° N to 70° N. Figure 1 (top) shows that COLs that occurred at latitudes lower than 45° N are more frequent during spring (AMJ) and summer (JAS) for those years when the vortex decays earlier. The monthly analysis (Fig. 1, bottom) portrays a perceptible transition during May. In the first four months of the year there are not significant differences in the COLs frequency according to the vortex persistence, but from May onwards COLs are more frequent when the stratospheric vortex decays earlier. This higher frequency persists until September and is particularly prominent during the summer period.

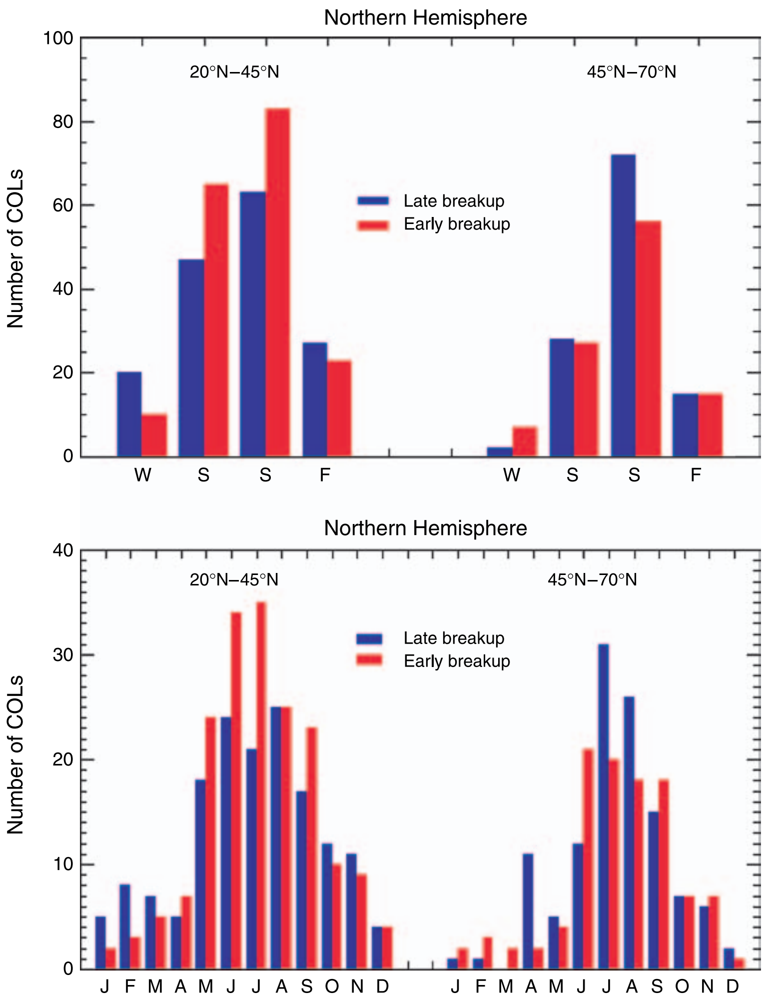

Fig. 1. Seasonal and monthly COLs occurrence for the five earlier (red) and later (blue) breakup years according to the combined B06-K05 for two latitude bands (20° N–45° N included) and (45° N–70° N excluded) (bottom). Differences in the occurrence from May to September were statistically significant at $p<0.05$ for monthly COLs occurrence for latitudes lower than 45° N (with the exception of August)

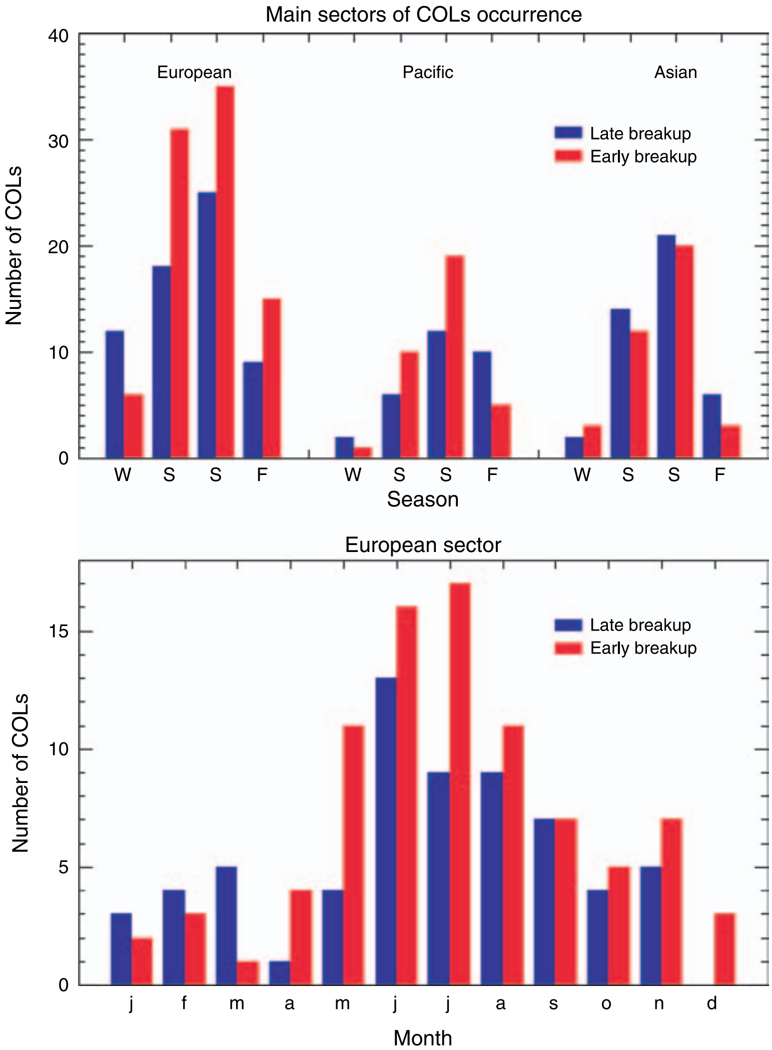

Fig. 2. As in Fig. 1, but for the main sectors of COLs occurrence found in Nieto et al (2005) and the monthly occurrence limited only to the European sector. Differences in the occurrence from May to August were statistically significant at $p<0.10$ for monthly COLs occurrence in the European sector

A *t*-Student test showed that, with the exception of August, the differences in the occurrence from May to September were statistically significant at $p<0.05$. Unlike for latitudes lower than 45° N, there are not significant differences in the monthly COL occurrence for latitudes higher than 45° N, although during July and August more COLs occur for later breakup years. The higher occurrence of COLs during spring and summer for earlier breakup years is also observed for the European and the Pacific sectors (Fig. 2), two of the main sectors of COLs development, but not in the Asian sector (which is located at higher latitudes). The European sector deserves further analysis because it is the Northern Hemisphere region with higher frequency of COLs occurrence. Therefore we have also analyzed monthly differences for the European sector and results are very similar to those obtained for latitudes lower than 45° N, although the differences started in April. The *t*-Student test showed that the monthly frequency distributions for earlier and later breakup years, during the period that spans from May to August, were different at $p<0.10$.

4. Concluding remarks

We have performed an exploratory analysis of the effect of the timing of stratospheric vortex breakup in the COL occurrence in the Northern Hemisphere. As there is large internal variability in the breakup of the Arctic vortex, there could be important dynamical differences between years with earlier and later breakups that could affect COLs occurrence, mainly the summerlike state after the vortex decay and the number of coherent potential vorticity structures formed in the following months after the breakup. To do this analysis we used the first multidecadal Northern Hemisphere COL database covering 41 years and different series of lower stratospheric vortex breakups. The analysis showed that:

The annual occurrence of COLs is very similar for those years with earlier vortex breakup for the whole Northern Hemisphere and for two of the main sectors of COLs occurrence, but different for the European sector, the Northern Hemisphere region with higher frequency of COLs occurrence. In the European sector, COLs are more frequent for earlier breakup years. This result seems to suggest a higher influence of the persistence of the vortex in the occurrence of COLs in the European sector than in the other two main sectors of COLs occurrence that could be due to the known displacement off the Pole of the Arctic stratospheric polar vortex toward Eurasia during late winter (Waugh and Randel, 1999; Karpetchko et al, 2005).

For latitudes lower than 45° N, the spring and summer COLs occurrence is, at least, partially controlled by the timing of the stratospheric vortex breakup, so in those years when the vortex decays earlier, there are more COLs in both seasons. The differences start in May and last until September, which coincides with the period when more COLs occur in the NH. These differences are statistically significant (with the exception of August) and they are particularly evident for the European sector, the area over the Northern Hemisphere with higher COLs occurrence.

For latitudes higher than 45° N, there are not significant differences in the COL occurrence according to the stratospheric vortex persistence, although during July and August more COLs occurred for later breakup years. These latitudinal discrepancies can reside in the different nature of the formation of lower latitudes COLs vs higher latitudes ones. According to Price and Vaughan (1992) higher-latitude COLs are not advected away from the main polar vortex as the lower-latitudes ones are, and they contain air of arctic and tropospheric origin. That could be the reason because these higher-latitudes COLs are less probable to occur because of remnants of the stratospheric vortex than the lower-latitudes are.

These results confirm that the earlier transition to summerlike dynamical state and the persistence of remnants of the vortex during earlier breakup years favor the conditions of lower latitudes COLs development since about one month of the breakup and that this influence persists for the whole summer. The timing of the stratospheric vortex breakup is easily calculated with only a few days of delay, therefore we believe that results here obtained have some predictive skill, by anticipating low occurrence of COLs, at lower latitudes, for late vortex decays and high occurrence for early decays.

Acknowledgments

We thank Robert X. Black and A. Karpetchko for providing data on stratospheric vortex breakup dates and the FCT of Portuguese Ministry of Science (SFRH/BPD/22178/2005), the Xunta de Galicia and the Spanish Ministry of Education and Science for granting the stays of R. Nieto and L. Gimeno in the ‘‘Centro de Geofísica da Universidade de Lisboa’’ through the programs ‘‘Bolsas para estadias no estranxeiro’’ and ‘‘Programa nacional de ayudas para la movilidad de profesores de universidad e investigadores españoles y extranjeros’’.

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