ELSEVIER

Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 1797–1812

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

A new diagnostic of stratospheric polar vortices

Luis Gimeno[a,*,1], Laura de la Torre[a], Raquel Nieto[a,1], David Gallego[b], Pedro Ribera[b], Ricardo García-Herrera[c]

[a]*Departamento de Física Aplicada, Facultad de Ciencias de Ourense, Universidad de Vigo, Ourense, Spain*
[b]*Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide de Sevilla, Sevilla, Spain*
[c]*Departamento de Física de la Tierra, Astronomía y Astrofísica II, Universidad Complutense de Madrid, Madrid, Spain*

Received 25 September 2006; received in revised form 26 July 2007; accepted 30 July 2007
Available online 7 August 2007

Abstract

We studied the main climatological features of the Arctic and Antarctic stratospheric vortices, using a new approach based on defining the vortex edge as the 50 hPa geostrophic streamline of maximum average velocity at each hemisphere. Given the use of NCAR-NCEP reanalysis data, it was thought advisable to limit the study to the periods 1958–2004 for the Northern Hemisphere (NH) and 1979–2004 for the Southern Hemisphere (SH). After describing the method and testing sample results with those from other approaches, we analysed the climatological means and trends of the four most distinctive characteristics of the vortices: average latitude, strength, area, and temperature. In general terms, our results confirm most of what is already known about the stratospheric vortices from previous studies that used different data and approaches. In addition, the new methodology provides some interesting new quantifications of the dominant wavenumber and its interannual variability, as well as the principal variability modes through an empirical orthogonal function analysis that was performed directly over the vortex trajectories. The main drawbacks of the methodology, such as noticeable problems characterising highly disturbed stratospheric structures as multiple or off-pole vortices, are also identified.

Keywords: Stratospheric polar vortices; Climatological features; Interannual variability

1. Introduction

The most distinctive feature of the circulation of the winter stratosphere is a large cyclonic vortex centred close to the winter pole (Haynes, 2005). The strong circumpolar westerly circulation associated isolates the air inside the vortex, resulting in reduced mass exchanges with the exterior. Since the well-known climatology of the polar vortices presented by Baldwin and Holton (1988), there has been considerable interest in studying certain characteristics of the vortex, such as its inner mean temperature, area, shape, and intensity. This interest has led to a number of studies documenting the vortex's characteristics. The different vortex climatologies depend mainly on two factors: the data used and the procedure for defining the vortex edge.

The NCAR-NCEP reanalysis data (Kalnay et al., 1996) is the dataset used most widely in previous

*Corresponding author.
E-mail address: l.gimeno@uvigo.es (L. Gimeno).
[1]Also at Centro de Geofisica (CGUL), Departamento de Fisica, Facultad de Ciencias, Universidad de Lisboa, Lisboa, Portugal.

1364-6826/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2007.07.013

works on vortices, but in recent years there have been comprehensive studies that used the ECMWF 40-year reanalysis (ERA40, Simmons and Gibson, 2000). The known weaknesses of the NCAR-NCEP reanalysis (Trenberth and Stepaniak, 2002) do not seem to produce important disagreements with ERA40. The consistency of the climatological structures of the stratospheric polar vortices between two studies (Karpetchko et al., 2005; Waugh and Randel, 1999) that used reanalysis data from ERA40 and NCEP/NCAR suggests that the main characteristics of the stratospheric vortex are independent of the dataset.

The methods based on potential vorticity (PV) are the procedures used most commonly to define the vortex (Karpetchko et al., 2005; Waugh and Randel, 1999; Waugh et al., 1999). Among them, the most common approach is that developed by Nash et al. (1996), who defined the vortex edge as the location of maximum PV gradients constrained by the location of maximum wind speed calculated around the PV isolines. Alternatively, the vortex can be characterised by studying zonal winds alone. In this case, the standard approach is based on computing the zonal-mean zonal wind at some pressure level (typically from 10 to 50 hPa) and at a latitude close to the core of the stratospheric vortex (typically 70°N or 60°S) (Black et al., 2006). This second method of analysis can describe vortex characteristics such as its strength. However, it cannot describe other important aspects, such as its area, its shape, its shifts off the pole, or the wavenumber of the polar night jets.

As a result of the efforts to characterise the vortices, their general structure is moderately well understood (e.g. Waugh et al., 1999; Harvey et al., 2002). It is now well established that the vortices are strongest in mid-winter; about mid-January for the Northern Hemisphere (NH) and mid-July for the Southern Hemisphere (SH), with larger gradients of PV for the SH in all seasons. Due to the stronger upward planetary wave flux, the Arctic vortex is more disturbed, warmer, and less persistent than the Antarctic one. Moreover, the Antarctic vortex is stronger and much more pole-centric than the Arctic one. Due to the presence of the stationary Aleutian anticyclone, the NH vortex shifts off the pole to its southeast, with the vortex centre frequently being located at 60°N and between 0° and 90°E (shifted off to Eurasia). Larger vortices are colder and stronger in the Arctic, but not in the Antarctic. There seems to be no relationship between the temperature and strength of the vortex.

A significant interannual variability of several characteristics of the vortex can be found in the literature. During the 1990s, the Arctic vortex was stronger, colder, and more persistent than in the 1980s, and this led many scientists to think in terms of possible trends (e.g. Zhou et al., 2000). However, in recent years, the vortex has been relatively warm and weak. Apart from the variations of the 1990s, the Arctic stratospheric vortex has remained fairly constant in all of its parameters since the early 1960s. Calculations of trends that include the years after 2000 show no trend for strength, area, temperature, or persistence (Karpetchko et al., 2005). The strength of the Antarctic vortex has increased since the late 1970s and its inner temperature has decreased. This result seems to be robust, and has been observed in reanalysis and achieved by several methods (Karpetchko et al., 2005; Renwick, 2004). Although there are some differences in magnitude between the two cited reanalyses and other observational sets of data, such as radiosondes (Connolley and Harangozo, 2001; Marshall, 2002), the trend towards increased strength and lower inner temperature is supported by theoretical expectations (Thompson and Solomon, 2002) that suggest that ozone loss is responsible for the increments in vortex strength and coldness. Destruction of the ozone also seems to be related to the higher persistence of the Antarctic vortex, which has been observed in both NCAR-NCEP (Waugh et al., 1999) and ERA40 data (Karpetchko et al., 2005). The single characteristic of the Antarctic vortex in which no trend is evident is area; this is probably due the small effect of the loss of ozone on the vortex position (Bodeker et al., 2002).

Currently, the most recent and comprehensive studies of the polar vortices make use of PV approaches. However, even these methodologies have certain disadvantages (Steinhorst et al, 2005). The PV is a highly derived quantity and, furthermore, is very sensitive to slight variations in its distribution. So, it could be useful to have a criterion based solely on the wind field to define the vortex. The aim of the study reported herein was to test the ability of a different approach, recently developed for the characterisation of the SH tropospheric jet streams by Gallego et al. (2005), to characterise the stratospheric vortices. Our main objective was to assess the capacity of this method to reproduce already-known structures but using geopotential alone. However, the method also opens up a number of new possibilities, such as estimating the vortex wavenumber directly or to analyse its main variability modes by using empirical orthogonal functions (EOFs). These possibilities are also investigated.

2. Data and method

The study was based on the daily average 50 hPa geopotential height from the 2.5° latitude–longitude NCEP/NCAR reanalysis (Kalnay et al., 1996). At the time of writing, this dataset starts at 1948 for both hemispheres. However, to minimise the effects of the lack of data (Kistler et al., 2001) the study period was limited to 1958–2004 for the NH and 1979–2004 for the SH.

In the study reported herein, the procedure of vortex detection, originally developed for the SH troposphere, was applied directly to the 50 hPa level to test its performance when describing stratospheric circulations. A complete description of the detection algorithm may be found in Gallego et al. (2005) and only a summary is provided here. The procedure starts by computing the field of 50 hPa geostrophic streamlines at each hemisphere. For every streamline encircling the entire hemisphere, the average latitude and geostrophic wind along its path are computed. The use of the geostrophic approximation instead of the real wind is based on the requirement of a closed path. However, the geostrophic approximation demands that a limit for the minimum latitude of a path be set. In practice, we select a conservative threshold and streamlines crossing 20°S or 20°N were discarded. Two more constraints on the possible vortex candidates are added: (1) no streamlines entering the polar cap limited by 85°N or 85°S were considered and (2) the wind vector over any portion of a selectable streamline was not allowed to lie within 140° of the westward direction. These constraints prevent consideration of the closed streamlines circulating around mid-latitude pressure centres, but limit the possible vortex candidates to those going eastward and having the geographic pole inside their path. The constraints did not seriously limit the analysis of tropospheric jet streams (in fact, they were designed to exclude spurious detections of jet streams) but they can constitute a too stringent filter when applied to the stratospheric vortex. A comprehensive analysis of the results for 2002 resulted in the addition of a fourth condition, according to which a minimum average velocity of $15\,\mathrm{m\,s^{-1}}$ was required for a streamline to be considered a vortex. A similar value has recently been used to characterise the boreal vortex circulation (Karpetchko et al., 2005). Unless specified otherwise, the results reported herein do not include vortices detected below this threshold. Finally, the streamline at each hemisphere of the maximum average velocity that fulfilled the four conditions was considered to be the edge of the stratospheric vortex.

As an example of the kind of results obtained with the methodology described above, Fig. 1 shows a vortex detection in the NH (a) and the SH (b). The average latitude and velocity of every streamline that fulfilled the three first constraints are displayed on the right. The streamline of maximum velocity is marked by an arrow and its corresponding path is displayed over the map. It clearly fulfils the fourth constraint; otherwise, the selected path would not be considered to represent the detection of a vortex. Though not assured by construction, usually all zonal wind maxima around the hemisphere are connected by the selected streamline as can be seen in Fig. 1. This fact provides a physically meaningful path for the vortex and its local velocity.

3. Main drawbacks of the method and comparison with other approaches

The procedure was designed to be as simple as possible, by using a minimum set of input variables (a method based on the geopotential data only), and the finding of the closed streamline around the pole, which present the maximum averaged geostrophic velocity. The method needs several "*ad hoc*"-imposed constraints that are necessary to yield meaningful and homogeneous results, which constitutes an evident drawback. These constraints eliminate, right from the very beginning of the analysis, some structures in the stratosphere as off-pole or double jets that are potentially important. However, the most important drawback of the method is the fact that the streamlines are not really material lines, so the polar vortex edge identified with our approach could not be always a transport boundary. The isolation of the polar air from mid-latitude air is, in consequence, better reproduced by approaches based on PV, the strong PV gradients separate the air inside the vortex from the surrounding surf (Nash et al.,1996). However, PV

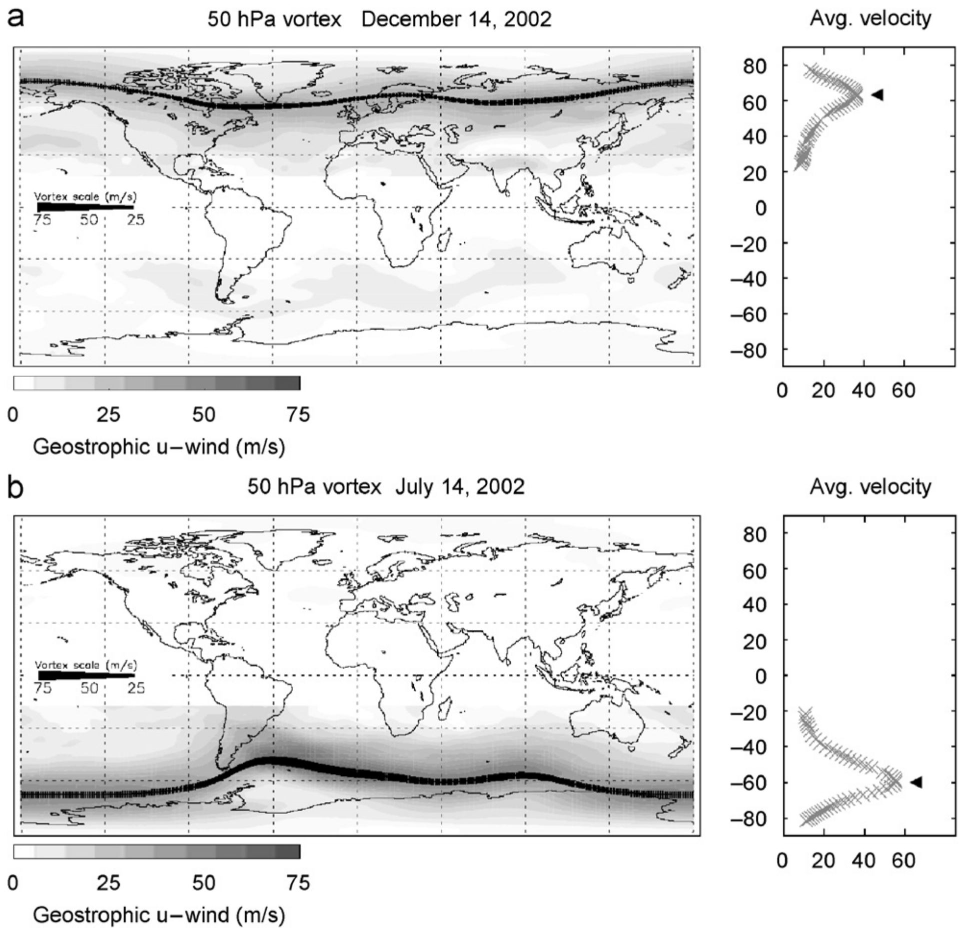

Fig. 1. Example of detected vortices for the NH (a) and SH (b). Right panels show the average velocity ($m\,s^{-1}$) of the streamlines encircling an entire hemisphere with an arrow pointing to the maximum. The corresponding streamline of maximum average velocity is displayed on the map. Grey shading indicates zonal geostrophic velocity (not represented for the 15°S–15°N interval).

approaches have also known drawbacks: in essence, the position of the maximum of PV gradient is more a measure of impenetrability of the polar vortex than of the polar vortex edge, which requires constraints based on the proximity of the polar jet (a knowledge of the location of the maximum of the wind jet). Sometimes the location of both maxima differs (Manney and Sabutis, 2000), mainly at the beginning and around the end of the winter. Furthermore, if there is no pronounced maximum of PV gradients and/or the wind peaks are not high enough ($15.2\,m\,s^{-1}$ in Nash et al., 1996), the vortex edge cannot be defined or it could be found an ‘‘apparent edge’’ that may vary considerably from one day to the next. This higher variability in the vortex edge calculated from the Nash et al. (1996) criterion can be present even when the PV gradient is moderate, so Steinhorst et al. (2005) showed variations of the edge of up to 20° of equivalent latitude from day to day, making the area smaller or greater. Chan et al. (1989) noted that the vortex edge could vary up to 10° in latitude in 4 days only due to the variation of the wind maximum and that there are times when the jet core is simply not identifiable, making the determination of the vortex boundary impossible. Another known drawback of approaches based on gradients of PV is its incapacity of determining the vortex edge in situations of double-peaked jets (Manney and Sabutis, 2000). In these cases the Nash et al. (1996) criterion finds a very broad or a very small vortex jumping between these two peaks from one day to the next. The existence of important (but not always the same) drawbacks in the different approaches to estimate the polar vortex edge gives value to our method as a complementary way of studying different features of the polar vortices.

To look for a comparison of our method with existent methodologies, a correlation analysis was performed by computing the averaged series of several vortex characteristics (Table 1) to identify where discrepancies among methods could be more manifest. Two main sets of parameters were chosen for comparing strengths, temperatures, and area of the vortex during the more active stratospheric vortex months (January, February, and March for the NH and August, September, and October for the SH):

Zonal-mean averages for zonal wind at 10 and 50 hPa (U10 and U50) at 70°N for the NH and 60°S for the SH were computed from the NCAR reanalysis, as well as area averages for the temperature at 10 and 50 hPa (T10 and T50) inside the polar cap limited by the latitudes 70–90°N (NH) and 60–90°S (SH). It is not possible to represent the area with zonal-mean parameters.

Results are based on the analysis on PV performed by Karpetchko et al. (2005) at the 475 K isentropic level. This study provides results for vortex strength and area. In addition, these authors compute the vortex temperature by two methods, one based on the Nash boundaries (Nash et al., 1996, designated as K05-N in Table 1) and the other defining the vortex by contours of constant PV (K05-PV in Table 1). Due to the length of the period analysed by Karpetchko et al. (2005), the comparison is limited to 2001.

Correlation coefficients in Table 1 show that the three approaches provide very similar patterns of development of the vortex with respect to temperature and strength in the NH, while the developments with respect to area are not correlated significantly. In the SH, the correlations between temperature and strength show slightly lower values than their NH counterparts, especially for strength. In contrast to the NH, the SH area exhibits very similar patterns of development under the two schemes compared. The poor agreement in the comparison of the areas of the frequently disturbed NH vortex suggests a deep difference between our approach and that of Karpetchko et al. (2005) under disturbed conditions (in the NH the vortex is highly variable) or a consequence of the fact that the streamlines calculated in our method are not really trajectories. The high correlation between the vortex areas in the SH may result from the known fact that the southern vortex is less variable and then the streamlines may approach trajectories.

It is possible to evaluate this difference by comparing the methodologies under low/high disturbed conditions, as displayed in Figs. 2 and 3, respectively. To perform this comparison, the PV values of Lait (1994) were used because they are reduced to a single isentropic level (420 K). This reduction allows the use of a single PV scale, thus making comparison among levels easier. Strong PV gradients represent the horizontal boundary of the polar vortex. Fig. 2 shows a case of a well-developed and strong polar vortex detected on 10 January 1996 at 12 UTC. In this case, the polar vortex detected by our approach matches well with the PV vortex at higher isentropic levels. The strength and

Table 1
Correlation coefficients between our approach and the zonal-mean average (NCEP10 and NCEP50) and Karpetchko et al. (2005) approaches (K05-N and K05-PV) for vortex temperature, strength, and area

		Temperature		Strength		Area			
		T10	T50	K05-N	K05-PV	U10	U50	K05	K05
NH	January	–	0.94	0.93	0.96	0.81	0.90	0.81	–
	February	–	0.94	0.97	0.97	0.70	0.88	0.84	–
	March	–	0.81	0.89	0.92	0.56	0.80	0.87	–
SH	August	–	0.81	–	–	0.53	0.87	–	0.76
	September	0.69	0.74	0.59	–	–	0.80	0.58	0.93
	October	0.79	0.92	0.84	0.88	–	–	–	0.86

Only correlations significant at $p<0.01$ are displayed. See text for details.

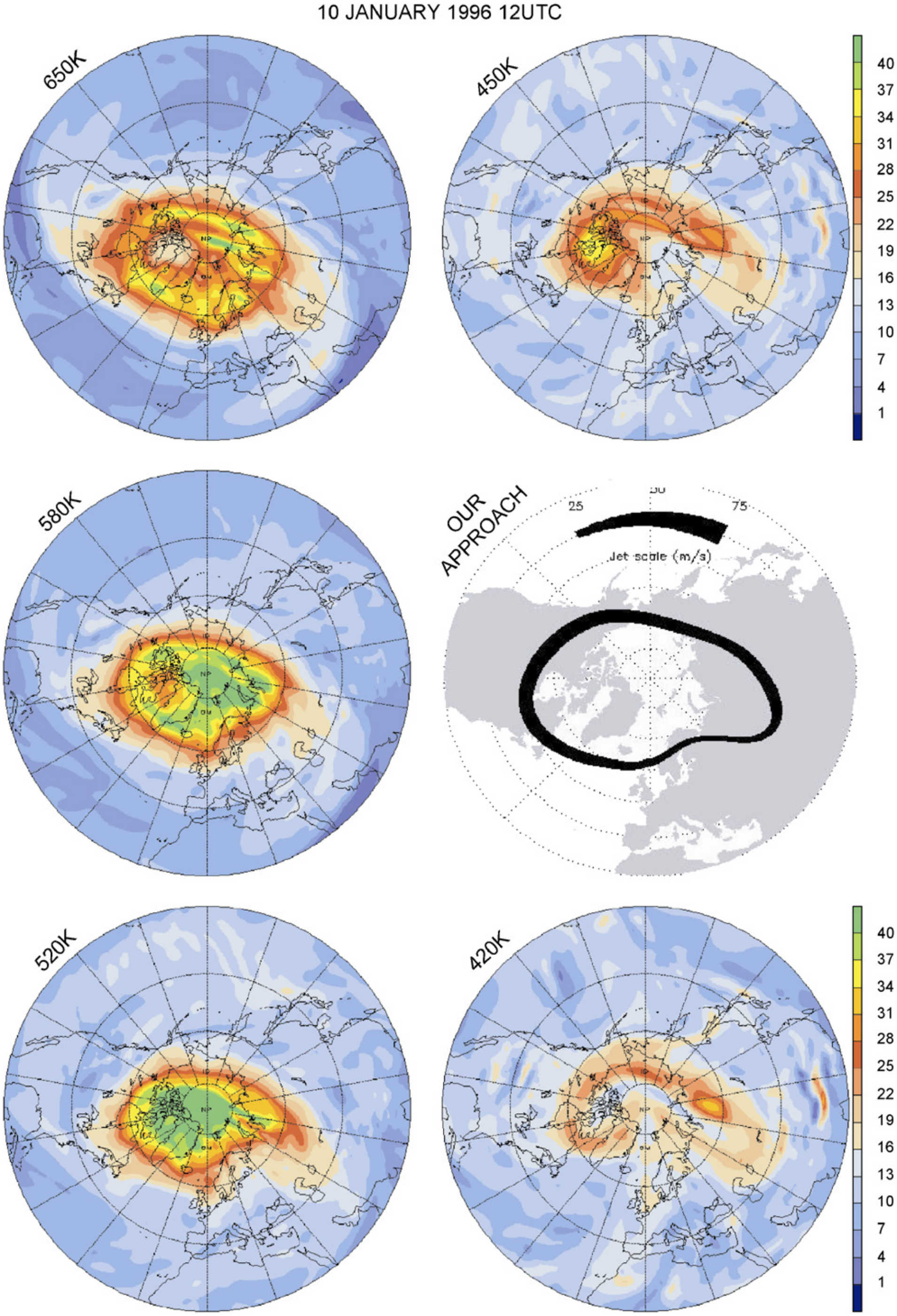

Fig. 2. Example of a well-defined, pole-centric vortex calculated by our approach and the distribution of potential vorticity at different isentropic levels (10 January 1996 at 12 UTC).

the area detected by both approaches are in this case similar, with a light extension southward of the vortex edge in our proposed method due to the known position of the wind maximum typically a few degrees equatorward of the maximum of PV (Nash et al., 1996). However, Fig. 3 shows a case

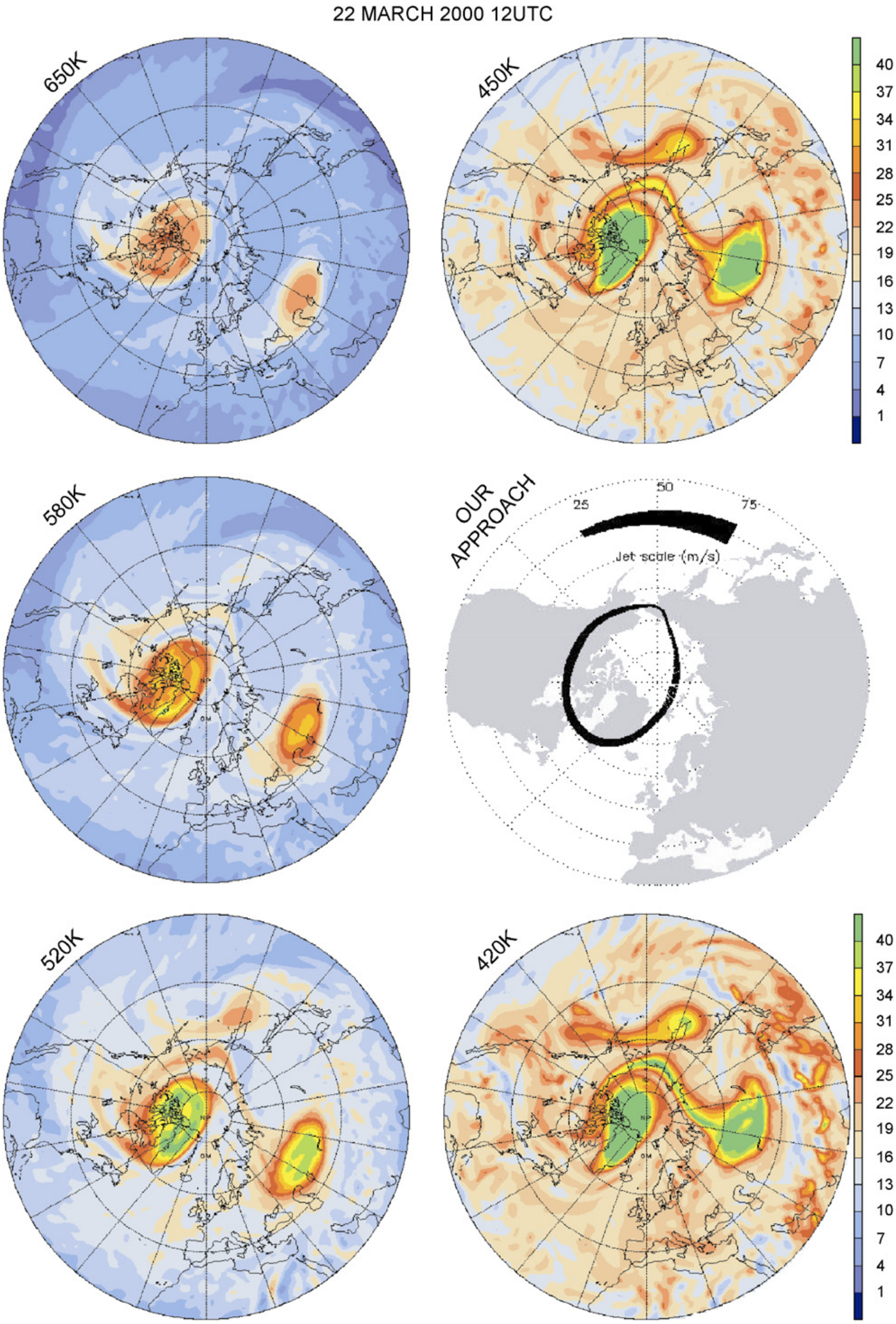

Fig. 3. Example of a disturbed vortex, displaced off the pole, calculated by our approach and the distribution of potential vorticity at different isentropic levels (22 March 2000 at 12 UTC).

(22 March 2004, 12 UTC) in which the vortex is not so well defined. PV maps show two different centres of PV. Our approach just considers the core of the major polar vortex. In the NH, situations in which the vortex is not so well defined are rather frequent in late winter and lead to large differences in the estimation of the polar vortex area between the two approaches.

4. Vortex climatology

4.1. Seasonal evolution

In our approach, every vortex consists of a set of coordinates (latitude, longitude, and velocity) that define its position and velocity for any given day. This representation allows a straightforward way of computing a basic climatology, such as that shown in Fig. 4. Note that only those months with vortex detection for more than 25% of the days have been included in the averages.

After the NH summer months, the first and the slowest ($20\,m\,s^{-1}$) vortex first appears at about 65°N, lowering its average latitude to 60°N during mid-winter as it reaches its largest average velocities ($40\,m\,s^{-1}$) and lower temperatures (211 K). From January on, as the vortex weakens, the latitude and temperature gradually increase to 65°N and 218 K, respectively. The SH velocity varies between $20\,m\,s^{-1}$ (March) and $65\,m\,s^{-1}$ (September), while the temperature drops from a December value of almost 230 K to a minimum in July of 205 K. Interestingly, while for the NH, vortex temperature and velocity display an out-phase seasonal evolution, in the SH, the maximum velocity lags the minimum temperature by 2 months. The progression of the latitude of the SH vortex over time is more complicated. From March until May, as the cold season begins, there is a poleward displacement of the average latitude from 58° to 62°S. Once the regime corresponding to the cold season is established completely, a slow decrease in latitude (equatorward displacement) is observed. This slow decrease lasts until August. From this time on, and similarly to the NH case, as spring advances the vortices slowly displace to the pole and by January the warm season regime is established completely. Finally, concerning the pattern of progression of the area, these results provide evidence that, in monthly averages, the area mostly reflects the changes in the average latitude, with poleward-displaced vortices resulting in lower areas and vice-versa. However, it must be stressed that this is not the case for daily values, because the area depends strongly on the displacement from the pole of the vortex centre and on its wave-like character. This fact plays an important role when computing strongly shape-dependent parameters, such as the vortex temperature.

One clear advantage of our algorithm is the possibility of defining easily a criterion to characterise the vortex wavenumber on a daily basis, because each vortex is considered a single structure. Such a classification can be made efficiently by decomposing each jet path in a Fourier series. The principal wavenumber characterising a jet was estimated by the harmonic component of maximum amplitude. As an example, Fig. 5 shows the composite of the three first wavenumbers. It is worth noting that even in this highly smoothed representation—because of the averaging of a large number of vortices—the characteristic wavenumber is still clearly evidenced. The larger amplitudes of the NH waves and the greater SH vortex speeds are also noticeable. Fig. 6 shows the seasonal distribution of each wavenumber. Both vortices display a clear predominance on wavenumber 1 vortex, with

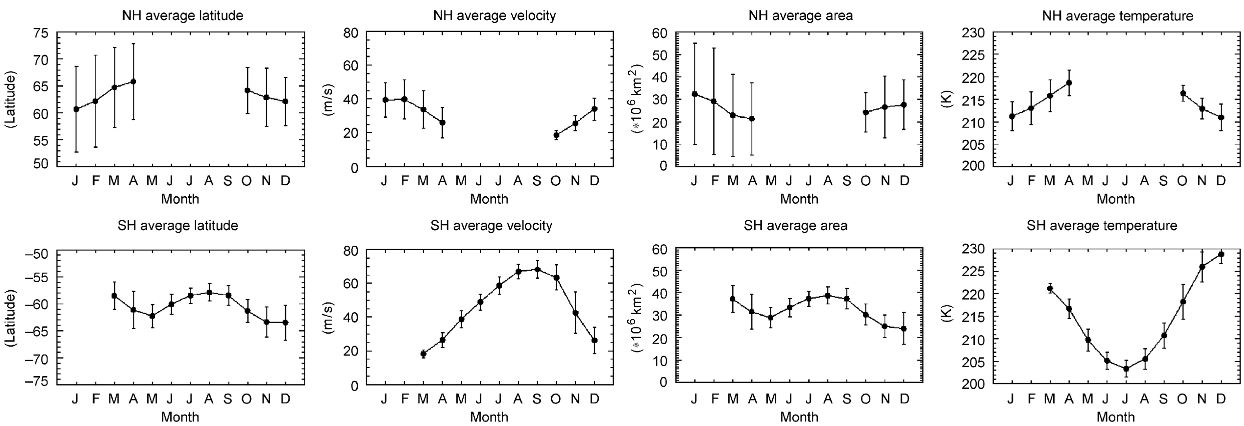

Fig. 4. Seasonal averages for latitude, velocity, area, and temperature for the NH (upper panels) and SH (lower panels). Error bars indicate ± 1 standard deviation of the monthly averages. Only months with a vortex detection of at least 25% of the maximum possible number of days are represented.

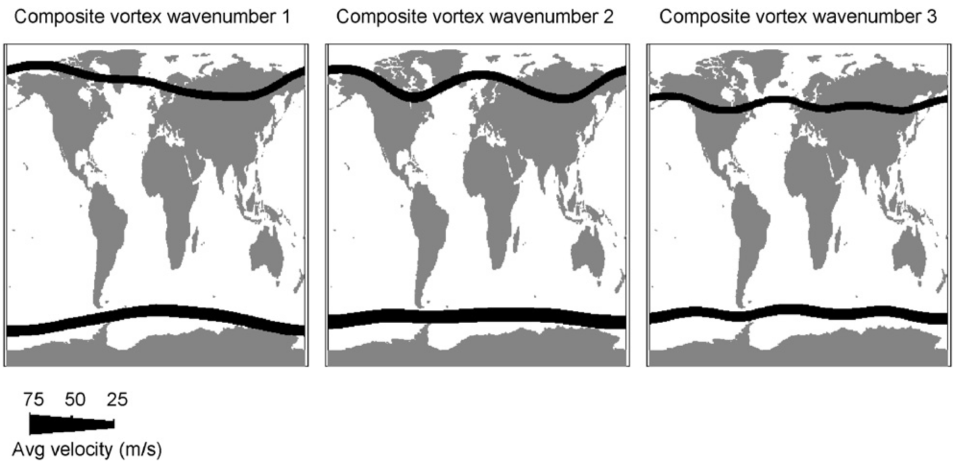

Fig. 5. Annual composite of the vortex for cases classified as wavenumbers 1–3 for the period 1958–2004. The average vortex velocity at each longitude is represented by the linewidth.

values from 60% to 85%. However, interesting differences between the hemispheres can be appreciated. For example, the percentage of wavenumber 3 and successive vortices are negligible in the NH, while in the SH wavenumber 3 vortices account for up to 10% of the cases for most of the active season and even a significant number of wavenumber 4 vortices are found during March. This does not necessarily reflect a more disturbed SH vortex but an easier screening of the components of higher wavenumbers for the SH vortices due to its more zonal path compared with its NH counterpart, as it was clearly evidenced in Fig. 5. So, if on a given day the vortex is mainly zonal but for a slight wavenumber 3 component, a case relatively frequent in the SH, the vortex will be classified as "wavenumber 3". In the NH, low wavenumbers (1 and 2) are extremely dominant compared with higher wavenumbers and the components with wavenumber 3 or 4 are almost in every case hidden by the vortices of longer wavelengths. However in the SH, small deviations from its much more zonal path are more evidenced and though wavenumbers 1 and 2 are clearly dominant as well, there are a significant number of cases (around 10%) in which wavenumbers 3 or even 4 are that of maximum amplitude. The NH shows a fairly constant distribution of wavenumber 1 and 2 vortices throughout the year, with only a small increment of wavenumber 2 vortices from November to January and a consequent decrease of wavenumber 1. The SH shows a clearer seasonal signal. There is a fall in the number of wavenumber 1 vortices during the winter in favour of wavenumber 2 and, to a lesser extent, wavenumber 3 vortices.

4.2. Trends

Fig. 7 shows the year-to-year variations for the winter averages for latitude, velocity, and temperature, based on the periods from December to March for the NH and from July to October for the SH. The annual series (not shown) produces almost identical results. The progression of the area enclosed by the vortex has not been included because in temporal averages, it represented mostly the changes in average latitude (see Section 4.1).

The NH vortex shows substantial year-to-year variations for latitude, strength, and temperature. The average latitude is around 63°N, and it has fluctuated noticeably over the years. Thus, while some winters were characterised by vortices with an average latitude equatorward of 60°N (1969–70, 1998–99, or 2003–04), it is possible to find cases poleward of 65°N, mainly during the first half of the study period (1967–68 or 1970–71). Overall, there is a significant trend ($p<0.05$) of $0.5^\circ\,\mathrm{decade}^{-1}$ towards the equator . This trend does not seem related to changes in velocity. However, despite the consequent trend to greater areas of vortices displaced towards the equator, the NH vortex shows the well-known decrease in the stratospheric temperature inside the boreal vortex, quantified as $-0.5\,\mathrm{K\,decade}^{-1}$, although this trend is due almost exclusively to the strong decrease during the

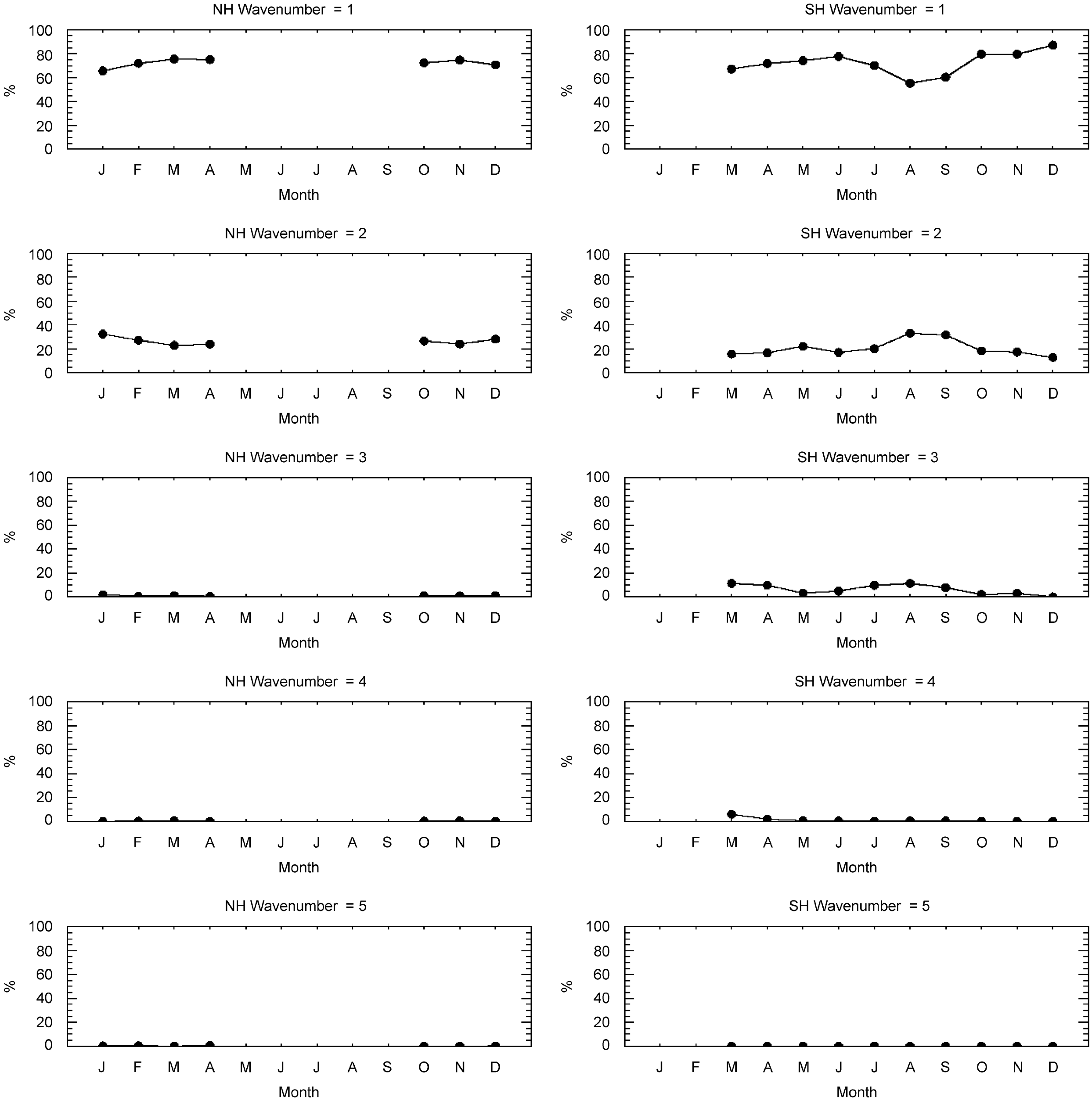

Fig. 6. Seasonal distribution (as a percentage of the total number of detected vortices) stratified by wavenumber for the periods 1958–2004 (NH) and 1979–2004 (SH).

1958–78 period of $-1.4\,\mathrm{K\,decade^{-1}}$ (concentrated mainly in the 1970s), with the decrease in the period 1979–2004 being more stable at $-0.1\,\mathrm{K\,decade^{-1}}$. The SH exhibits much lower year-to-year fluctuations for the three analysed variables and no significant trends were detected. However, in contrast to the NH case, the SH vortex also shows a tendency to poleward latitudes of 0.5° latitude per decade, which is not significant due to the shorter study period.

The time evolution of the wavenumbers 1–3 distribution is shown in Fig. 8. The Arctic vortex can vary strongly from year to year. For example, the winters of 1968–69 or 1977–78 were clearly dominated by wavenumber 1 vortices with frequencies of 95% and 89%, respectively, while other

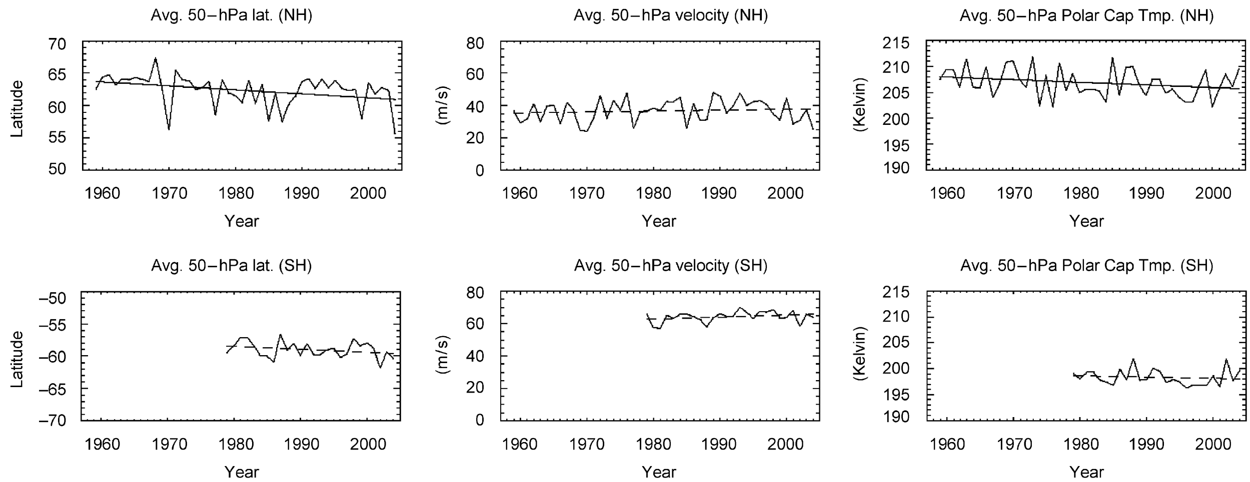

Fig. 7. Annual progression and trends for the wintertime average latitude, velocity, and temperature inside the stratospheric vortex for the periods 1958–2003 (NH) and 1979–2004 (SH). Statistically significant trends ($p<0.05$) are indicated as continuous lines.

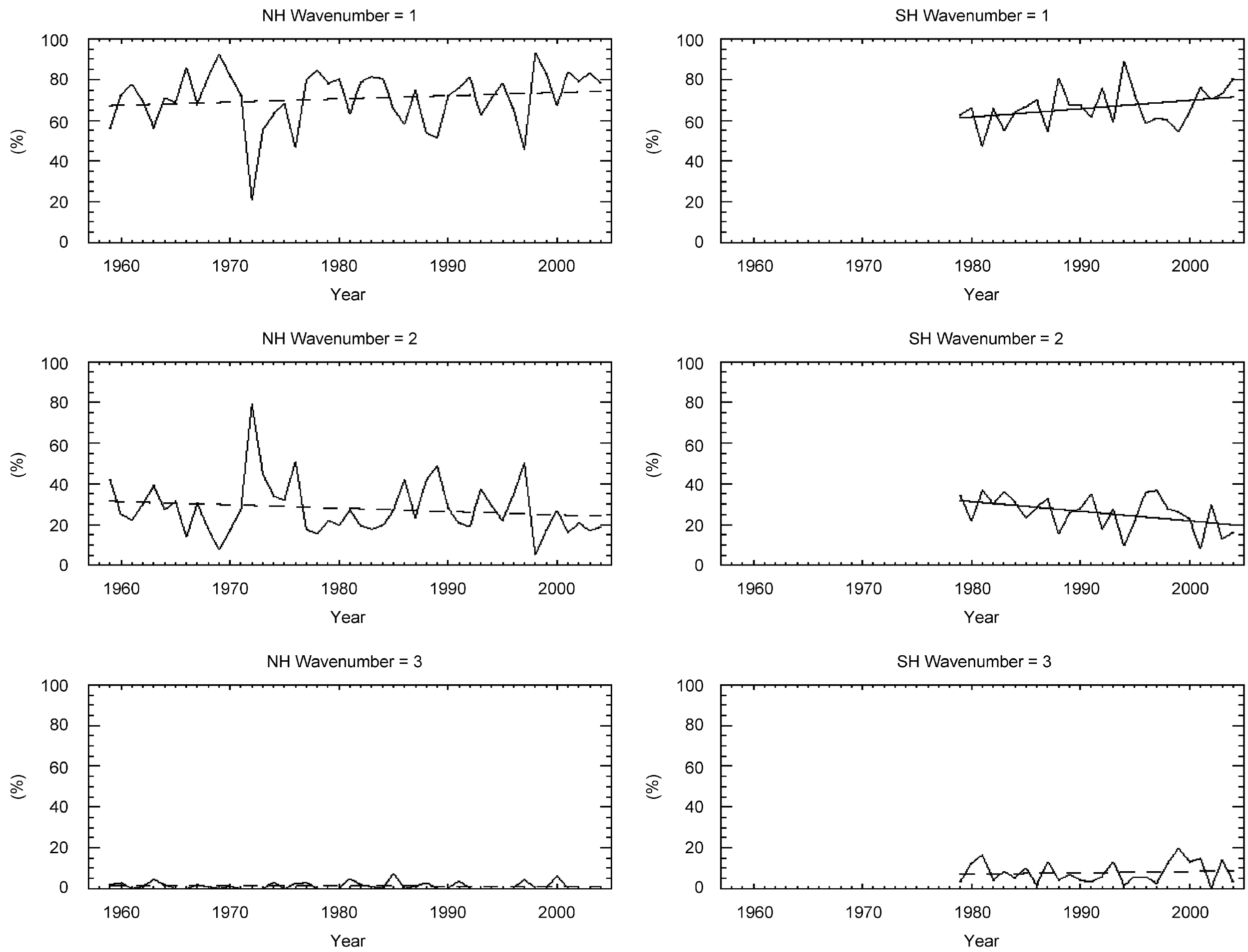

Fig. 8. Wintertime progression and trends of the relative frequency of the vortex stratified by wavenumber for the periods 1958–2003 (NH) and 1979–2004 (SH). Significant trends ($p<0.05$) are represented by continuous lines.

years, such as 1971–72 or 1996–97, present comparable values for wavenumbers 1 and 2. The interannual variability is markedly lower in the SH, although some years in the mid-1990s show wavenumber 2 slightly greater than average. The relative importance of wavenumber 3 is seen in Fig. 6, which reaches values up to 10% of the total number of vortices is now evidenced to be rather stable in time. Finally, it must be pointed out that the significant positive trend for wavenumber 1 seems to be compensated by a decrease of wavenumber 2 in the wintertime averages.

4.3. EOF analysis

Fluctuations in the stratospheric polar jets can be characterised by representing deviations of the zonal-mean flow from the climatology. In this study, we used as input data the deviations from the climatology of the latitude and intensity (measured by the local velocity) vortex path and used EOFs to find the main modes of variability. In order to avoid including the annual cycle, a daily climatology smoothed with a 31-day running mean filter was removed from the raw data. This analysis was performed for daily values from November to March during the period 1958–2004 in the NH, and for daily values from April to October during the period 1979–2004 in the SH.

In Figs. 9 and 10, EOF coefficients for the first and second principal components (PCs) for the latitude and intensity of the vortex are shown as a function of the longitude. In terms of latitude (Fig. 9) the results indicate that for both hemispheres the main variability mode (EOF1) displays the same sign around the globe. This fact indicates that latitudinal displacements and any portion of the vortex tend to affect to the entire structure and in consequence EOF1 corresponds to expansion/contraction. This mode explains almost half of the total variance for the NH (46.1%) and a quarter for the SH (25.7%). EOF2 corresponds to the displacement

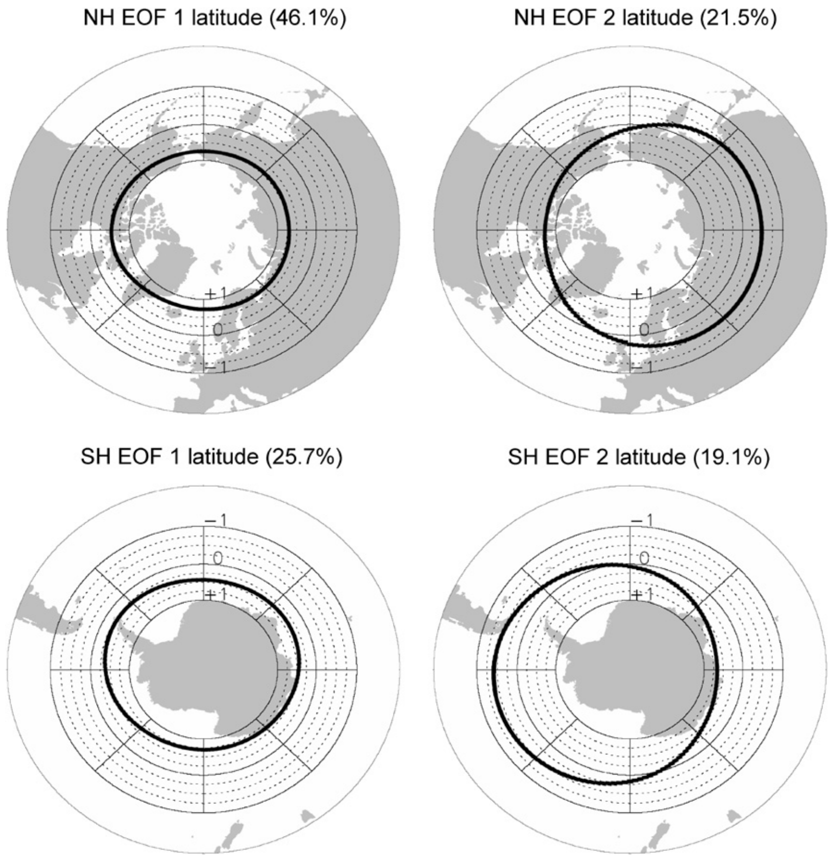

Fig. 9. EOF coefficients of the first and second principal components of vortex latitude as a function of the longitude for both hemispheres. Weights are displayed on a scale from -1 to $+1$ (ticks every 0.25). Explained variance is given in brackets.

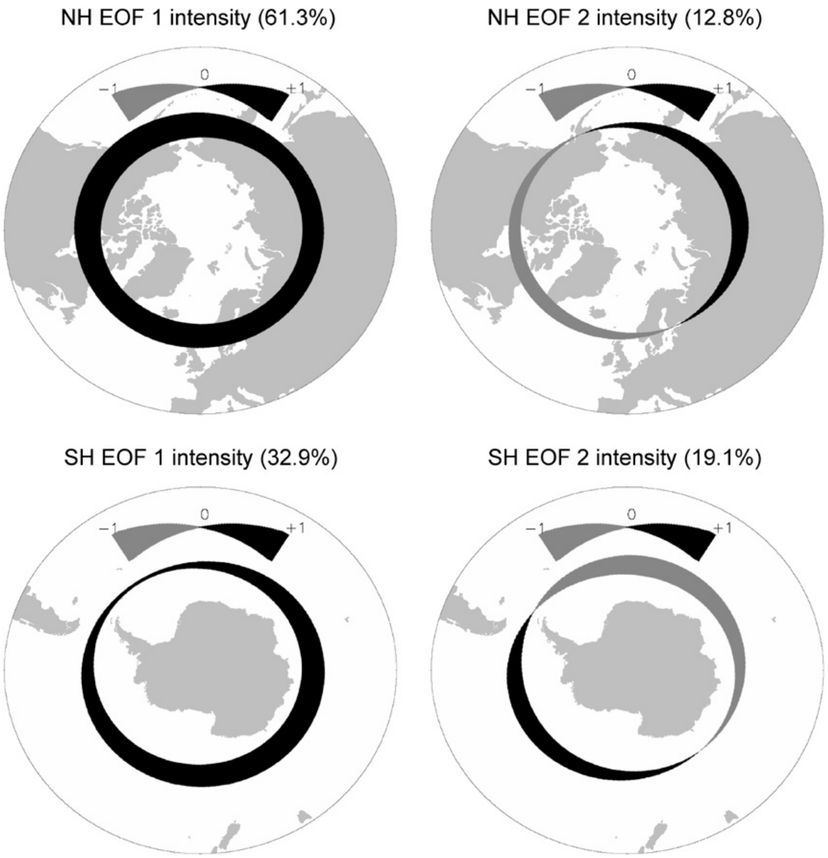

Fig. 10. EOF coefficients of the first and second principal components of vortex intensity as a function of the longitude for both hemispheres. Weights are displayed as linewidth from −1 to 0 (grey) and 0 to +1 (black). Explained variance is given in brackets.

of the vortex from the pole. The second most important mode of variability for the NH vortex (21.5% of the variance) is a displacement between Eurasia and North America, while for the SH, EOF2 (19.1% of variance) shows that the displacement occurs between the Indian and Pacific Oceans. Fig. 10 shows the EOF analysis for intensity. In this representation, the line thickness represents the corresponding weight of the EOF component at each latitude, with the colour indicating the sign. For example, EOF1 for the NH shows large and positive values at every longitude so this mode represents a simultaneous change in the vortex strength as a whole. EOF2 for the NH shows weights of opposite sign depending on the longitude, so this mode indicates that when the vortex is strengthened over Eurasia, it weakenes over North America and vice-versa. In this way, in terms of intensity in both hemispheres, EOF1 corresponds to vortex intensification/weakening along every longitude, while EOF2 represents a wavenumber 1 perturbation of the vortex velocity. This general description fits both hemispheres, although there are some interesting differences. In the NH, the first PC of the intensity explains 61.3% of the total variability and leads to a general increase in the velocity of the vortex as a whole (and vice-versa) (the EOF in the Arctic contains only signals of variability of the vortex strength). However, for the SH, there are far larger asymmetries between longitudes and the main mode for intensity explains only 32.9% of the variance. In the SH, intensification/weakening of the vortex occurs mostly over the Indian and the Pacific Oceans (coefficients above 0.5), and are barely related to variations over the Atlantic (coefficients below 0.3). This means that the EOF in the Antarctic vortex contains both signals of variability of vortex strength and wave perturbation. The second mode of intensity variability corresponds to the redistribution of velocity along the vortex. The total variance explained by the EOF2 for intensity is rather low

(12.8% for the NH and 19.1% for the SH). When the vortex tends to increase its velocity over the east coast of North America, it exhibits lower velocities over East Asia and vice-versa. In the SH, opposite changes in intensity occur, mostly between Africa and the Pacific.

The correlation analysis among PCs shows that for the NH, the contractions/expansions are related only slightly to the general speeding up of the vortex ($r = +0.36$ between EOF1 for position and intensity) and the displacement from the pole is related to the redistribution of velocity reaching a correlation of 0.50 between EOF2 for position and intensity. For the SH, no significant correlations between PCs are found, so it would seem that there is no connection between changes in position and velocity.

5. Summary and concluding remarks

We have outlined the main climatological features of the Arctic and Antarctic vortices using a new approach based on defining the vortex edge as the 50 hPa geostrophic streamline of maximum average velocity. Our approach allows the analysis of the characteristics of the stratospheric vortices that could previously only be studied when using PV approaches, but using the simplest variable, geopotential alone.

We compared the new results with those of previous studies. For the Arctic vortex, our results agree well with those of previous studies for temperature and strength, but do not agree well for area. For the SH, there is good agreement regarding area for the whole winter and only moderate agreement for temperature and strength. On a daily basis, the differences could be very important for those days on which the vortex is not well defined or disturbed. The climatological structures of both vortices derived from our approach are consistent with previous climatologies obtained from different datasets and approaches. The Antarctic vortex is larger, stronger, and colder than the Arctic one. The Arctic and Antarctic vortices have a similar seasonal progression and the results confirm those of previous studies, where it was found that the vortex is strongest, coldest, and largest in both hemispheres in mid-winter (January in the NH and August in the SH). Area, strength, and temperature have a clear seasonal cycle, rising (decreasing) until mid-winter and then decreasing (rising) progressively until the vortex breaks down.

The analysis of trends with respect to vortex characteristics shows some agreement, but also important disagreements with previous studies. Although the Antarctic vortex is larger, colder, and stronger than the Arctic, the Antarctic interannual variability is smaller than in the Arctic, in part due to the general absence of extreme events, when the vortex is very deformed in the SH. Our study confirms the results of previous studies in this regard (Waugh and Randel, 1999; Karpetchko et al., 2005). On the other hand, our trend calculations show that during the period 1958–2004, the Arctic vortex became larger and colder. This contrasts with results obtained by Karpetchko et al. (2005), who did not show any significant trend in the Arctic vortex characteristics. However, the results of our calculations are in agreement with the results of other previous studies, such as that conducted by Randel and Wu (1999), where it was found that colder vortices are linked to ozone depletion. Our results do not show significant trends in the temperature and strength of the Antarctic vortex that have been reported in previous studies and that are sometimes attributed to ozone depletion (Randel and Wu, 1999). As all the studies concerning trends in the polar vortices characteristics, our results should be carefully linked to the intrinsic drawbacks of the method. Because our method misses the identification of a highly disturbed vortex, the computed variance is reduced (especially in the Arctic vortex), and the estimated trends could be only representative of those well-developed and non-perturbed vortices.

Besides the results that were already known, the particularities of the new approach, especially the assimilation of the vortex as a closed streamline, has allowed the quantification of some characteristics that are difficult to assess by using PV methods.

First, a fast Fourier transform analysis revealed an increase of wavenumber 1 vortices during winter in both hemispheres. Although further analysis should be performed, this increment could be related to increases in the planetary waves entering the stratosphere that correspond closely to the weakening of the polar vortices. In linear theory, the probability that planetary waves will propagate upward depends on the zonal wind speed, the vertical structure of the atmosphere, the latitude, and also the wavenumber (Charney and Drazin, 1961). Under normal conditions, only ultra-long planetary waves could propagate into the stratosphere, which in our analysis would be vortices with wavenumber 1. In addition, the percentage of wavenumber 3 and higher wavenumber vortices are negligible in the NH, while in the SH wavenumber 3 vortices account for about 10% of the cases for most of the active season. This result is important and merits further study, taking into consideration the results of Song and Robinson (2004), which showed the importance of the wavenumber 3 waves for the downward influence of the stratosphere on the stratosphere. The analysis of wavenumber also has to be interpreted keeping in mind that our method was built from wind maxima. The polar vortex edge could be lightly equatorward of the maxima of PV, the wavenumber analysis being sometimes more representative of the wave structure outside the vortex than inside. So the ''observed'' wave in our method could not penetrate the vortex and could not be fully representative in terms of erosion of the polar vortex.

Second, an EOF study performed directly over the vortex path quantified the variance associated with the main variability modes. The main fluctuations of the vortices are (i) an expansion/contraction that is accompanied by vortex intensification/weakening and (ii) a displacement of the vortex off the pole that is accompanied by a redistribution of the velocity within the vortex. Given that the fluctuations were estimated by means of EOFs and are consequently orthogonal by construction, this result supports those of previous studies, where little correlation was found between the displacements off the pole and the large elongation of the vortices (Waugh and Randel, 1999). There are important differences between the Arctic and Antarctic vortices. The expansion/contraction of the Arctic vortex is more longitudinally symmetric and explains much more variance than the equivalent in the Antarctic one. In fact, the expansion in the SH is accompanied by a deformation over the 35–250° longitude and is not associated with changes in the strength of the vortex. The displacement off the pole is the second most important mode of variability for both hemispheres, the Arctic vortex is shifted off the pole towards Eurasia, which is in accordance with the results of previous studies (Karpetchko et al., 2005). This displacement is associated with a redistribution of the velocity within the vortex, which increases over the eastern coast of North America and decreases over East Asia. The Antarctic vortex is also displaced off the pole, mainly in the sector around 90° and −90° longitudes (which is coincident with the Atlantic displacement reported in previous studies, such as Waugh and Randel, 1999 or Karpetchko et al., 2005). This displacement explains more variance than the equivalent in the NH, but is not associated with a redistribution of the velocity within the vortex.

Summarising, at climatological scale, the new methodology seems to reproduce rather well the known characteristics of the stratospheric circulations in both hemispheres. In addition, it provides interesting options, such as the possibility of estimating the vortex wavenumber or quantifying its variability modes by EOF analysis applied directly to the vortex trajectories. The strong reproduction of known characteristics, plus the additional options, makes this kind of approach very promising and attractive for determining vortex characteristics at daily resolution. However, the direct ''translation'' of an algorithm developed for use in the troposphere has three important drawbacks, which in order of importance are: (1) the definition of polar vortex edge does not always result in a measure of the impenetrability of the vortex; (2) the method needs a stringent requirement of discarding off-pole vortices, which excludes some important cases from the study from the very beginning; and (3) the methodology does not consider two or more vortices by hemisphere. These limitations are particularly important in the NH case, especially during transitional seasons. With respect to these factors, approaches based on PV analysis are currently superior to our methodology, but our method is useful as a complementary tool, since it highlights vortex features uncovered by the PV methods. Developments that will address these limitations are currently underway. It is hoped that they will yield a complete methodology for stratospheric vortex analysis. If this is achieved, there will probably be an improvement upon the current study of events, such as the sudden stratospheric warmings and/or vortex breakdown, that depend strongly on knowledge of the precise location and shape of the vortex at daily scales.

Acknowledgements

This work was supported by the Spanish Ministry of Education and Science under the project TROJET (CGL2005-07288-C05). We thank Alexey Karpetchko for providing data on the stratospheric vortex and the Xunta de Galicia, the FCT of Portuguese Ministry of Science (SFRH/BPD/22178/2005) and the Spanish Ministry of Education and

Science for granting the stays of R. Nieto and L. Gimeno in the CGUL through the programmes ''Bolsas para estadias no estranxeiro'' and ''Programa Nacional de ayudas para la movilidad de profesores de universidad e investigadores españoles y extranjeros''. The authors also thank reviewers for their useful comments to the original manuscript.

References

Baldwin, M.P., Holton, J.R., 1988. Climatology of the stratospheric polar vortex and planetary wave breaking. Journal of the Atmospheric Sciences 45, 1123–1142.

Black, R.X., McDaniel, B.A., Robinson, W.A., 2006. Stratosphere–troposphere coupling during spring onset. Journal of Climate 19 (19), 4891–4901.

Bodeker, G.E., Struthers, H., Connor, B.J., 2002. Dynamical containment of Antarctic ozone depletion. Geophysical Research Letters 29 (7), 1098.

Chan, K.R., Scott, S.G., Bui, T.P., Bowen, S.W., Day, J., 1989. Temperature and horizontal wind measurements on the ER-2 aircraft during the 1987 Airborne Antarctic Ozone Experiment. Journal of Geophysical Research 94, 11,573–11,587.

Charney, J.G., Drazin, P.G., 1961. Propagation of planetary-scale disturbances from the lower into the upper atmosphere. Journal of Geophysical Research 66, 83–109.

Connolley, W.M., Harangozo, S.A., 2001. A comparison of five numerical weather prediction analysis climatologies in southern high latitudes. Journal of Climate 14 (1), 30–44.

Gallego, D., Ribera, P., Garcia-Herrera, R., Hernandez, E., Gimeno, L., 2005. A new look for the Southern Hemisphere jet stream. Climate Dynamics 24, 607–621.

Harvey, V.L., Pierce, R.B., Fairlie, T.D., Hitchman, M.H., 2002. A climatology of stratospheric polar vortices and anticyclones. Journal of Geophysical Research 107 (D20), 4442.

Haynes, P.H., 2005. Stratospheric dynamics. Annual Review of Fluid Mechanics 37, 263–293.

Kalnay, E., Coauthors, 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77, 437–471.

Karpetchko, A., Kyro, E., Knudsen, B.M., 2005. Arctic and Antarctic polar vortices 1957–2002 as seen from the ERA-40 reanalysis. Journal of Geophysical Research 110, D21109.

Kistler, R., et al., 2001. The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bulletin of the American Meteorological Society 82 (2), 247–268.

Lait, L.R., 1994. An alternative form for potential vorticity. Journal of the Atmospheric Sciences 51, 1754–1759.

Manney, G.L., Sabutis, J.L., 2000. Development of the polar vortex in the 1999–2000 Arctic winter stratosphere. Geophysical Research Letters 27, 2589–2592.

Marshall, G.J., 2002. Trends in Antarctic geopotential height and temperature: a comparison between radiosonde and NCEP-NCAR reanalysis data. Journal of Climate 15 (6), 659–674.

Nash, E.R., Newman, P.A., Rosenfield, J.E., Schoeberl, M.R., 1996. An objective determination of the polar vortex using Ertel's potential vorticity. Journal of Geophysical Research 101, 9471–9478.

Randel, W.J., Wu, F., 1999. Cooling of the Arctic and Antarctic polar stratospheres due to ozone depletion. Journal of Climate 12, 1467–1479.

Renwick, J.A., 2004. Trends in the Southern Hemisphere polar vortex in NCEP and ECMWF reanalyses. Geophysical Research Letters. 31.

Simmons, A.J., Gibson, J.K., 2000. The ERA-40 project plan. Era-40 Project Report Series 1.

Song, Y., Robinson, W.A., 2004. Dynamical mechanisms for stratospheric influences on the troposphere. Journal of the Atmospheric Sciences 61, 1711–1725.

Steinhorst, H.-M., Konopka, P., Günther, G., Müller, R., 2005. How permeable is the edge of the Arctic vortex: model studies of winter 1999–2000. Journal of Geophysical Research 110, D06105.

Thompson, D.W.J., Solomon, S., 2002. Interpretation of recent Southern Hemisphere climate change. Science 296 (5569), 895–899.

Trenberth, KE., Stepaniak, D.P., 2002. A pathological problem with NCEP reanalysis in the stratosphere. Journal of Climate 15, 690–695.

Waugh, D.W., Randel, W.J., 1999. Climatology of Arctic and Antarctic polar vortices using elliptical diagnosis. Journal of the Atmospheric Sciences 56, 1594–1613.

Waugh, D.W., Randel, W.J., Pawson, S., Newman, P.A., Nash, E.R., 1999. Persistence of the lower stratospheric polar vortices. Journal of Geophysical Research 104, 27191–27202.

Zhou, S.T., Gelman, M.E., Miller, A.J., McCormack, J.P., 2000. An inter-hemisphere comparison of the persistent stratospheric polar vortex. Geophysical Research Letters 27, 1123–1126.