Identification and ERA-15 Climatology of Potential Vorticity Streamers and Cutoffs near the Extratropical Tropopause

HEINI WERNLI
Institute for Atmospheric Physics, University of Mainz, Mainz, Germany, and Institute for Atmospheric and Climate Science, ETH Zürich, Zurich, Switzerland

MICHAEL SPRENGER
Institute for Atmospheric and Climate Science, ETH Zürich, Zurich, Switzerland

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ABSTRACT

A novel approach is introduced to identify potential vorticity (PV) streamers and cutoffs as indicators of Rossby wave breaking near the extratropical tropopause and to compile climatologies of these features on different isentropic surfaces. The method is based on a contour searching algorithm that identifies the dynamical tropopause [2 potential vorticity units (PVU; PVU = 1 × 10^{-6} Kg^{-1} m^{2} s^{-1}) isoline] on isentropic surfaces. The contour is then analyzed to search for cutoffs and filament-like streamers. Whereas the identification of cutoffs is unambiguous, the one for streamers requires the specification of two parameters that determine the width and length of the contour feature to be classified as a streamer. This technique has been applied to the PV distribution in the Northern Hemisphere on isentropes from 295 to 360 K during the time period from 1979 to 1993 using the 15-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-15).

The climatology reveals a pronounced zonal asymmetry in the occurrence of PV streamers and cutoffs. On all isentropes considered there are clear frequency maxima whose location changes with altitude. For instance, in winter and on the 300-K isentrope, stratospheric streamers and cutoffs occur most frequently near 50°–60°N over the western side of Canada and Siberia. On higher isentropes, the maxima are located farther south and at the downstream end of the storm-track regions. Considering continental areas, the Mediterranean appears as a region with particularly abundant PV features.

1. Introduction

An early depiction of Rossby wave breaking (RWB) near the extratropical tropopause is given by Berggren et al. (1949; reproduced in Rossby 1959). It shows a Rossby wave train that propagates over the North Atlantic, amplifies, and undergoes nonlinear wave break-
poleward (e.g., Nielsen-Gammon 2001). The two types of wave breaking are also referred to as equatorward and poleward RWB, respectively. Frequently, the PV tongues are further stretched into narrow filaments, so-called PV streamers, that eventually break up into distinct PV cutoff vortices (Appenzeller and Davies 1992; Browning 1993; Appenzeller et al. 1996). Here, as in Appenzeller et al. (1996), the term stratospheric PV streamer/cutoff refers to stratospheric features on isentropic surfaces (PV > 2 PVU; 1 PVU = 1 × 10⁻⁶ K kg⁻¹ m² s⁻¹), and the term tropospheric PV streamer/cutoff is used for their tropospheric counterparts (PV < 2 PVU). These flow elements are a manifestation of Rossby wave breaking occurring near the extratropical tropopause.

The study of Bleck and Mattocks (1984) was an early (if not the first) study that presented isentropic PV charts with pronounced equatorward extending stratospheric tongues and introduced the notion of stratospheric “streamers.” Since then, many theoretical, diagnostic, and observational investigations have been devoted to this subject. The following paragraphs provide a brief summary of (i) the theoretical background of streamer and cutoff formation, (ii) the observational evidence for their existence and structure, and (iii) some particular issues that highlight the relevance of these flow features for, for instance, stratosphere–troposphere exchange, the generation of near-tropopause turbulence, heavy precipitation events and the triggering of convection, tropical–extratropical interactions, and the formation of atmospheric blocking and ozone miniholes.

From a theoretical point of view, the formation of stratospheric PV streamers is an integral part of one archetypal category of baroclinic life cycles. Dry baroclinic waves can lead to the formation of equatorward extruding stratospheric PV streamers if they evolve in a jetlike environment characterized by a predominant anticyclonic barotropic shear component (e.g., Davies et al. 1991; Thornicroft et al. 1993). Although these idealized studies clearly show that PV streamers can evolve because of dry dynamical processes alone, in some real case situations, upstream diabatic heating and the induced negative PV tendencies in the upper troposphere might be crucial for the occurrence of their formation (Massacand et al. 2001). Nakamura and Plumb (1994), using the highly idealized framework of contour advection, investigated the effect of the jet profile on wave breaking and found that zonal jets usually favor the occurrence of equatorward RWB. Focusing on poleward RWB events, Peters and Waugh (1996) performed contour advection calculations and confirmed the important role of meridional shear also for the evolution of poleward protruding tropospheric streamers. Several idealized studies have analyzed the stability and breakup of streamerlike vortices (e.g., Juckes 1995; Wirth 1996; Fehlmann 1997). It was found that the evolution of the vortices depends critically on both the ambient flow and the structure of the streamer itself. In addition to their purely dynamical stability properties, the development of near-tropopause PV streamers in the real atmosphere can be influenced, for instance, through the interaction with the underlying topography and/or diabatically produced low-tropospheric PV anomalies (Morgenstern and Davies 1999; Hoinka et al. 2003).

Streamers of stratospheric air can be observed regularly from water vapor satellite imagery as dark filaments (Appenzeller and Davies 1992), due to the low moisture content of stratospheric air compared to the more humid tropospheric environment. However, the darkest area does not necessarily correspond to the location of the PV maximum on a certain isentrope. Downward motion might be most pronounced along the western flank of the streamer and upward motion might be induced below the center of the PV anomaly, leading to a nontrivial correspondence between isentropic PV and satellite-deduced upper-tropospheric humidity (Wirth et al. 1997; Liniger and Davies 2003). Water vapor satellite images also provide a spatially and temporally high-resolution view on the streamer instability and breakup process (Ralph 1996). The detailed vertical structure of PV streamers has been analyzed using, for instance, mesosphere–stratosphere–troposphere (MST) radar data (Vaughan and Worthington 2000), ozone lidar (Vaughan et al. 2001), and water vapor lidar (Hoinka et al. 2003). These observations indicate the presence of turbulence that causes mixing between stratospheric and tropospheric air.

Stratospheric and tropospheric streamers and cutoffs are regarded as key midlatitude flow structures that are frequently associated with intense stratosphere–troposphere exchange (e.g., Hoskins et al. 1985; Appenzeller et al. 1996; Sprenger and Wernli 2003). This is because of several reasons: (i) PV streamers are often associated with steep tropopause structures (sometimes folds) and large wind shear leading to clear-air turbulence and hence small-scale three-dimensional mixing; (ii) the horizontal breakup process of the streamer into one or several cutoff vortices is irreversible and associated with intense quasi-isentropic mixing; and (iii) cutoff vortices frequently decay on relatively short time scales (1–2 days) through cloud diabatic erosion processes (e.g., Wirth 1995; Wirth and Egger 1999) and/or filamentation of the outer layers (Gouget et al. 2000). Several case studies have been undertaken to quantify
these processes and to assess the overall mass exchange between troposphere and stratosphere during a representative event of streamer formation, breakup, and decay (e.g., Kowol-Santen et al. 2000; Bourqui 2006). It is important to note that cutoffs do not always decay completely. Case studies suggest that sometimes the air in the cutoff can return to the reservoir of origin. For instance, in the study of O’Connor et al. (1999), who investigated a tropospheric filament over Europe, only about one-third of the subtropical tropospheric air mass was irreversibly transferred to the midlatitude lower stratosphere.

Studying examples of autumntime heavy precipitation events south of the Alps, Massacand et al. (1998) found that stratospheric PV streamers extending over western Europe into the Mediterranean act as precursors for heavy rain events. This relationship has been studied in more detail and quantified climatologically for the time period of 1957–2002 by Martius et al. (2006). The streamers evolve slowly and induce the steady advection of warm and moist air from the Mediterranean toward the southern slope of the Alps along their downstream flank. If the streamer reaches far south into the Sahara, it can induce the northward advection of both humid Mediterranean air as well as dry, potentially dust-laden, Saharan air masses toward the Alps (Sodemann et al. 2006). Furthermore, stratospheric streamers act to reduce static stability in the lower and midtroposphere. The importance of this process has been discussed by Waugh and Funatsu (2003), who studied the triggering of deep convection by stratospheric streamers that reach deep into the tropical North Pacific. Other examples of tropical–extratropical interaction that involve stratospheric PV streamers are, for instance, the extratropical transition of hurricanes (Thornicroft and Jones 2000) and extreme precipitation events over Africa (Knippertz and Martin 2005).

According to Pelly and Hoskins (2003 and references therein), the essence of the buildup of atmospheric blocks is the poleward advection and subsequent cutoff of subtropical air masses induced by poleward RWB events. Independently from the issue of blocking, air parcels in tropospheric streamers and cutoffs are frequently of subtropical origin and characterized by low-ozone mixing ratios. Upon advection into midlatitudes, they can lead to significantly reduced ozone columns in the lower stratosphere. Several studies on the formation of transient ozone miniholes emphasize the important contribution from poleward RWB at tropopause level (e.g., Orsolini et al. 1994; Peters et al. 1995; Hood et al. 1999; Weber et al. 2002; Koch et al. 2005). Finally, it has been suggested that both phases of the North Atlantic Oscillation (NAO) arise from the breaking of synoptic-scale waves. The analyses of Benedict et al. (2004) indicate that the formation of pronounced anticyclonically breaking stratospheric streamers over western North America and the North Atlantic is crucial for the growth and maintenance of the positive NAO phase. Similarly, the negative phase is characterized by cyclonic wave breaking over the central North Atlantic leading to the generation of tropospheric streamers near Iceland. Also for the El Niño–Southern Oscillation phenomenon, it has been hypothesized (Shapiro et al. 2001) that equatorial wave breaking is strongly enhanced during the cold compared to the warm phase.

This brief summary shows the relevance of PV streamers and cutoffs and motivates the compilation of a climatology of these features. During recent years, several long-term studies have been conducted that define RWB either via the occurrence of reversed meridional PV gradients on isentropic surfaces (Baldwin and Holton 1988; Postel and Hitchman 1999; Waugh and Polvani 2000; Abatzoglou and Magnusdottir 2004) or with the aid of contour advection calculations (Morgenstern and Carver 1999; Scott and Cammas 2002). The former approach is computationally straightforward but can only identify tilted PV streamers and does not distinguish between streamers and cutoffs. The latter method is computationally expensive and focuses on very thin filaments that are typically not resolved by operational (re)analysis datasets. In this study, an alternative approach will be introduced and applied to the 15-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-15) in the Northern Hemisphere. The method is based mainly upon a contour identification algorithm and can distinguish between stratospheric and tropospheric streamers and cutoffs. Also, it is able to identify streamers independent from their orientation. This approach will be introduced in section 2 and some examples will be presented to illustrate the method’s functionality. Results from the 15-yr climatology will be shown in sections 3–5. Section 3 focuses on the geographical frequency distributions, section 4 on aspects of the seasonal cycle, and in section 5 the statistical relationship between individual PV features will be analyzed. The final section summarizes the main conclusions, discusses the caveats of the approach, and compares the results with previous climatologies of RWB. Also, an outlook is given on future extensions and applications of the study.

2. Datasets and methodology

In this section, the methodology and the underlying datasets are described and then illustrated in a case study.
a. Datasets

All analyses in this study are based upon the ERA-15 dataset covering the time period from 1979 to 1993 (Gibson et al. 1997). ERA-15 data were produced in the late 1990s using a T106L31 model resolution and the optimum interpolation data assimilation technique. The required fields (horizontal wind components and temperature) are available every 6 h on 31 vertical levels from the surface up to 10 hPa and have been interpolated onto a regular grid with 1° horizontal resolution. Secondary fields like potential temperature and PV have been calculated on the original hybrid model levels. Finally, the PV field was interpolated to a stack of isentropic levels from 295 to 360 K, separated by 5 K.

b. Identification of streamers and cutoffs

Two different algorithms have been implemented to identify PV streamers and cutoffs on isentropic surfaces. The one for streamers is based upon a contour searching algorithm and is described below. In contrast, the algorithm for cutoffs identifies two-dimensional regions of stratospheric or tropospheric air that are fully embedded within tropospheric or stratospheric air, respectively. For the identification of a stratospheric cutoff, the algorithm consists of the following steps: C1) starting at the equator and going poleward, the first grid point along a meridian is sought with a PV value larger than 2 PVU; C2) all neighboring grid points that are stratospheric (i.e., PV > 2 PVU) are identified and attributed to the potential cutoff. This two-dimensional search is continued until the entire cutoff structure is found; and C3) it is verified whether the identified structure extends over the pole. If it does, then the structure is not a cutoff but rather the main stratospheric body; if it does not, then the potential cutoff is finally classified as a stratospheric cutoff. At every grid point that belongs to the stratospheric cutoff, the variable \( C_s \) is set equal to 1. The search is then continued with step C1) along the next meridian until all stratospheric cutoffs at one time instant have been identified. For tropospheric cutoffs, the steps are very similar except that in step C1) the search starts at the pole and goes equatorward and in step C3) the potential cutoff is eliminated if it extends to the equator.

An important caveat is that vortices with PV larger than 2 PVU that are not of stratospheric origin but are produced by latent heat release due to condensation (e.g., Hoskins et al. 1985) or frictional processes near high mountains (e.g., Thorpe et al. 1993) are also identified by the algorithm. A clear distinction between stratospheric cutoffs and ephemeral diabatically produced PV anomalies is difficult and would require trajectory calculations to check for PV conservation. However, such an analysis is computationally expensive and has not been performed in the present study. It will turn out that on the lower isentropes considered, some identified PV cutoffs indeed appear to be related to the surface topography. However, because of their stationarity, they can be distinguished from stratospheric cutoffs (see section 3b).

For the identification of streamers, the 2-PVU contour that encircles the main stratospheric body (without the smaller-scale cutoffs) is identified (step S1). To this end, the same contour searching algorithm is used as in Wernli and Schwierz (2006) where it served to identify cyclones from the surface pressure field. Here, the algorithm determines a polygon of more than 1000 points along the 2-PVU contour that are separated by about 30 km. In a second step (S2), potential “base points” for streamers are identified. They are geographically close but connected by a long 2-PVU contour. Technically, for every pair of contour points it is checked whether (i) the direct spherical distance between the two points \( d \) is smaller than a certain threshold distance \( d < D = 800 \) km and (ii) the connection between the two points along the contour \( l \) is longer than a threshold \( l > L = 1500 \) km, as illustrated in Fig. 1. All these pairs of contour points are regarded as base points for streamers. In the final step (S3), the grid points that are enclosed by the direct connection of the two base points and the contour itself are determined (hatched region in Fig. 1). If they are stratospheric, then these points form a stratospheric streamer and the variable \( S_s \) is set to 1. If they are tropospheric, then it is a tropospheric streamer and the variable \( S_s \) is set to 1 at the streamer’s grid points.
and $S$, are either 0 or 1. Note also that the choice of the threshold distances $D$ and $L$ in $S_2$ is somehow arbitrary and the number of identified streamers depends upon the chosen values. With the values used here, the algorithm identifies meso- and synoptic-scale filamentary features but does not consider troughlike structures ($l$ not much larger than $d$; see Fig. 1) and tiny wiggles (small $l$) of the 2-PVU contour as PV streamers (see examples in next section).

c. Examples

As a first example, the PV distribution and the identification of streamers and cutoffs are considered at an arbitrary time instant (0600 UTC 29 June 1993) on three isentropes (320, 335, and 350 K) in the Northern Hemisphere (Fig. 2). First it is noted that the shape of the 2-PVU contour differs strongly on the three isentropes (Fig. 2a). On 320 K, the stratospheric body is relatively small and has a complicated shape and a broad-tailed filament extending over eastern Europe. Several cutoffs are present over Siberia, the Pacific, and Canada. Near northern Alaska there is a pair of adjacent tropospheric and stratospheric streamers. As shown in Fig. 2b, all these features are successfully identified by the algorithm; 15 K above, the tropopause is located roughly near 40°N and shows a narrow tropospheric streamer extending from Italy to north of Iceland and an embracement of a tropospheric streamer by two stratospheric ones southeast of the Urals. Another triple feature appears over central

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**Fig. 2.** The (a) PV distribution on 335 K (PVU; gray shading; bold black line for 2 PVU) at 0600 UTC 29 Jun 1993 and the 2-PVU contours on 320 K (white line) and 350 K (black line). The PV features identified by the algorithms on (b) 320, (c) 335, and (d) 350 K. The black line in (b)–(d) denotes the 2-PVU contour; the darker gray shading marks tropospheric streamers and cutoffs, and lighter gray shading marks stratospheric streamers and cutoffs.
Canada. Several small-scale stratospheric cutoffs are located over the Pacific and Atlantic Ocean, all captured by the algorithm (Fig. 2c). Note that all these features on 335 K hardly coincide with the streamers and cutoffs identified on the 320- and 350-K isentropes, indicating that they are vertically shallow. On 350 K, there are several small tropospheric cutoffs over the North Atlantic and a peculiarly shaped stratospheric streamer near Hawaii with neighboring features, two of them classified as tropospheric streamers (Fig. 2d) and one as a stratospheric cutoff. As an exception, the latter corresponds also to a cutoff on the lower 335-K isentrope (Fig. 2c). This example illustrates that the identification algorithms work well, and it also reveals the variability in size and shape of the identified PV features. Some of the streamers appear as fingerlike filaments; others are more complex and tend to occur in pairs or triple structures.

The second example (Fig. 3) shows a time series of identified PV streamers and cutoffs on 335 K from 1200 UTC 29 June to 1800 UTC 6 July 1993. It serves to further demonstrate the accurate identification of the PV features and to highlight the richness of the possible temporal evolutions of PV streamers and cutoffs. The classical paradigm (Appenzeller et al. 1996) that a streamer breaks up into one or several cutoffs that subsequently decay is only one out of many possible developments. For instance, the tropospheric streamer over Europe at 0600 UTC 29 June (Fig. 2c) forms a tropospheric cutoff 6 h later (Fig. 3a), which slowly decays over eastern Europe during the next 4 days (Fig. 3b). The tropospheric streamer over central Asia in Fig.

![Fig. 3. Time sequence of the identified PV streamers and cutoffs on 335 K (gray shading as in Fig. 2) at (a) 1200 UTC 29 Jun, (b) 1200 UTC 3 Jul, (c) 1800 UTC 4 Jul, and (d) 1800 UTC 6 Jul 1993.](image-url)
3. Isentropic streamer and cutoff climatologies

The algorithms are applied to every time instant of the dataset on several isentropic surfaces and subsequently the streamer and cutoff fields $S_s$, $S_t$, $C_s$, and $C_t$ are temporally averaged. This results in 15-yr climatological frequency distributions of the PV features. Before presenting these climatologies on a selection of isentropes, some basic facts about the zonal mean potential temperature distribution and its seasonal cycle are briefly revisited.

The zonal and seasonal mean structure of the potential temperature field and the 2-PVU tropopause in the Northern Hemisphere undergo significant seasonal changes [see, e.g., Liniger and Davies (2004, their Fig. 1)]. During winter [December–February (DJF)], the 305–335-K isentropes cross the tropopause in midlatitudes ($30^\circ$–$60^\circ$N). During summer (June–August), there is a substantial shift and the 325–350-K isentropes intersect the tropopause in the same latitude range. The zonal mean 310-K isentrope, which crosses the tropopause near $45^\circ$N in winter, resides completely in the troposphere during summer. This seasonal variability is mainly due to the general seasonal cycle of temperature in the extratropics and needs to be taken into account when interpreting and comparing isentropic frequency fields of PV features during different seasons. Clearly, a streamer and cutoff climatology should not be restricted to a single or a few isentropes.

a. Stratospheric and tropospheric streamers during winter

Figure 4 presents the winter mean (DJF) climatological distribution of stratospheric and tropospheric streamers on different isentropes. A value of 5% indicates that at this location a streamer was present during 5% of the considered time instants. The most notable features of the climatology are (i) the presence of latitudinal belts with strong zonal asymmetries, (ii) the change of the patterns with altitude, and (iii) the striking similarity of the distributions of stratospheric and tropospheric streamers with a meridional shift of $10^\circ$–$20^\circ$. The belts with maximum streamer frequency move toward the equator when going to higher isentropes. This is expected from the climatological zonal mean location of the tropopause that cuts lower isentropes near the pole and higher isentropes in the subtropics. Typically, stratospheric streamers are located slightly south of the intersection of the zonal mean tropopause (e.g., $45^\circ$N on 310 K; $28^\circ$N on 350 K) and tropospheric streamers slightly north of this latitude.

On 300 K, frequency maxima of stratospheric streamers occur over the Sea of Okhotsk (larger than 10%), in the Hudson Bay area, and over Finland (Fig. 4a). These regions correspond to the troughs of the wintertime stationary wave pattern. On 310 K, the frequency maximum extends from the Alps to the Aral Sea (Fig. 4b) with values up to 10%. Secondary maxima with frequencies of 5%–7% occur in the eastern North Pacific and over Newfoundland. Farther above, the deviations from zonal symmetry become even more pronounced and two maxima can be clearly seen, one in the European/Atlantic sector and the other one over North America and the eastern North Pacific. The former is located over the Mediterranean on 320 K (Fig. 4c), over the Canary Islands on 330 K (Fig. 4d), and over the subtropical central Atlantic on 340–350 K (Figs. 4e,f). Its amplitude decreases from about 9% on 320 K to about 6% on 350 K. The other maximum is located over the western United States on 320 K (Fig. 4c) and in between Hawaii and Baja California on 340–350 K (Figs. 4e,f) and has its largest amplitude on 330–340 K.

For tropospheric streamers, the zonal asymmetry and the zonal position of the frequency maxima are very similar to their stratospheric counterparts. The absolute frequency values of tropospheric streamers are, however, slightly lower, in particular on the lower isentropes considered. The general agreement between the climatological patterns of stratospheric and tropospheric streamers indicates that the scenario of pairwise occurrence of the two features (cf. the discussion of
Figs. 2 and 3) might be quite frequent. This issue will be considered quantitatively in section 5.

The fact that the frequency maxima on 320–350 K generally coincide with regions where the meridional potential temperature gradient on the tropopause is relatively weak [see, e.g., Fig. F1 in Källberg et al. (2005)] can be interpreted in 2 ways: streamers tend to occur in regions with reduced zonal wind speed, and/or the effect of streamers (and their subsequent breakup and decay) has a significant effect on the time-mean flow through the large-scale isentropic stirring of stratospheric and tropospheric air masses.

b. Stratospheric and tropospheric cutoffs during winter

The winter climatology of cutoffs is shown in Fig. 5. If cutoffs form mainly through streamer breakups, then the climatological distributions of the two features should be similar. This is indeed the case (cf. with Fig. 4), however with some notable differences. First of all, on 300 and 310 K the algorithm for stratospheric cutoffs identifies PV anomalies that are most likely produced because of near-surface diabatic processes (cf. section 2b). They occur on 300 K over the Sahara, near the Arabian mountains, and in the lee of the Rockies (Fig. 5a), and on 310 K very prominently north of the Himalaya (Fig. 5b). These frequency maxima should be regarded as artifacts of the methodology.

It is notable that on all levels, the climatological frequency of stratospheric cutoffs is smaller than that of stratospheric streamers. In contrast, on most levels tropospheric cutoffs are slightly more frequent than tropospheric streamers. For the stratospheric features, this might be due to a combination of different effects: (i) not all streamers break up and form cutoffs, (ii) cutoffs are typically smaller than streamers, and (iii) cutoffs may have a shorter lifetime because of rapid diabatic erosion. The difference in the frequency of stra-
spheric streamers and cutoffs is particularly obvious on 310 K over the central Pacific (streamer frequency of about 6% versus a cutoff frequency of about 2%; see Figs. 4b, 5b). The contrasting behavior of tropospheric features might be due to a more frequent breakup of the streamers and/or to a longer lifetime of tropospheric compared to stratospheric cutoffs. The latter would be qualitatively in line with the typical erosion processes for stratospheric and tropospheric cutoffs. Stratospheric cutoffs can decay through cloud condensational processes that are relatively intense and lead to rapid PV changes near the tropopause (Wirth 1995). Tropospheric cutoffs that are moist compared to their stratospheric environment can decay through radiative processes, which are less intense and generally change the PV distribution on slightly longer time scales (Zierl and Wirth 1997).

Looking at the location of the maxima in the streamer and cutoff frequency distributions, it becomes obvious that for stratospheric features they are roughly collocated, indicating that stratospheric cutoffs typically remain stationary. For tropospheric features the situation is similar on the 330–350-K isentropes. However, below the distributions of tropospheric streamers and cutoffs differ considerably: for instance, on 320-K, tropospheric cutoffs occur most frequently over Kazakhstan (Fig. 5c), well to the east of the maximum of tropospheric streamers (Fig. 4c). Here the interpretation is that tropospheric cutoffs form through the breakup of tropospheric streamers in regions of relatively strong westerlies that then advect these features downstream. On 310 K, the cutoff maximum is located over eastern Siberia (Fig. 5b), also downstream of the streamer maximum over western Siberia (Fig. 4b).

\( \textit{c. Streamers and cutoffs during summer} \)

The isentropic distributions of streamers and cutoffs reveal a significant seasonal cycle. This is on the one hand due to the seasonal cycle of the location of the isentropes but on the other hand also due to changes in the tropospheric dynamics [like, e.g., the reduced baroclinic wave activity in the North Atlantic and North
Pacific storm-track regions during summer (e.g., Wernli and Schwierz 2006).

Figure 6 presents summer climatologies of stratospheric and tropospheric streamers, again on a selection of isentropic surfaces. The cutoff distributions are not shown, since as in winter, they are similar to the ones for streamers. When comparing summer and winter climatologies, it is meaningful to select pairs of isentropes that intersect (in the zonal mean sense) the tropopause at similar latitudes (e.g., 300 K in winter and 320 K in summer, 310 K in winter and 330–340 K in summer, and 340 K in winter and 350–360 K in summer).

On 320 K in summer, stratospheric and tropospheric streamers occur mainly in bands near 50°–60°N and 60°–80°N, respectively (Fig. 6a) with reduced zonal variability compared to the winter distribution on 300 K (Figs. 4a, 5a). On 330 K (Fig. 6b), the pattern of stratospheric streamers looks very similar to the one in winter on 310 K (Fig. 4b). At higher levels (Figs. 6c,d) there appears again a strong zonal asymmetry with pronounced streamer maxima over the central and eastern

![Figure 6. Summer mean frequency (%) of streamers on (a) 320, (b) 330, (c) 340, and (d) 350 K for the ERA-15 time period of 1979–93. Gray shading is for stratospheric streamers and contours are for tropospheric streamers (CI is 2% starting from 1%).](image-url)
North Pacific, the Caribbean, and the North Atlantic. Generally, the summer maxima have a larger amplitude compared to the winter maxima (in particular for the cutoffs). This might be due to (i) a more frequent occurrence of Rossby wave breaking in summer, (ii) a larger size of individual streamers and cutoffs in summer, and/or (iii) a longer lifetime of the PV features in summer. It remains a subject of future investigation to determine the relative importance of these possibilities. Another notable difference between the winter and summer distributions is the vertical location of the absolute frequency maximum (on isentropes above 300 K). In winter it occurs on low isentropes (310–320 K) near the Mediterranean and in summer on 350 K in the subtropical regions mentioned above. This could be a result of the strong baroclinic wave activity during winter and the occurrence of summertime Rossby wave breaking events that are independent of midlatitude storm-track activity.

The climatological distributions have also been calculated for the intermediate spring and autumn seasons (not shown). The isentropic frequency patterns are similar to the ones during summer and winter, if the comparison is made between fields on appropriate isentropes. For instance, the distribution of stratospheric streamers on 330 K during autumn is very similar to the 320-K winter distribution, as well as to the one on 325 K during spring (except for a shift of the Mediterranean maximum farther to the west). On higher levels, the stratospheric streamer patterns on 340 K in winter, 350 K in autumn, and 345 K in spring show close resemblance; however, the amplitude of the Atlantic frequency maximum is largest in autumn and smallest in spring (about half of the autumn value). For the Pacific frequency maximum of stratospheric streamers, the seasonal differences are smaller.

4. The seasonal cycle

So far, seasonal mean geographical frequency distributions have been shown on different isentropes. Now we take a look at the seasonal cycle of the hemispherically integrated behavior of streamers and cutoffs as a function of potential temperature.

a. Time series on selected isentropes

Time series with monthly mean values of the hemispherically integrated frequency of PV streamers and cutoffs (Fig. 7) show the seasonal cycles and their interannual variability on the 350- (Figs. 7a–d) and 320-K (Figs. 7e–h) isentropes. Figures 7i–l depict a vertical average, as explained below. For every month, the values correspond to the averaged percentage of the hemisphere that is covered by a certain category of PV features. Typical values are about 1%, which is consistent with the frequency distributions shown in Figs. 4–6.

There is a distinct seasonal cycle on both isentropes. On 350 K, minimum and maximum frequencies of streamers and cutoffs are found in winter–spring and summer–autumn, respectively. Values in August are about 3–4 times larger than those in February, except for tropospheric cutoffs whose amplitude of the seasonal cycle is weaker (Fig. 7d). A particularly steep increase in the number of stratospheric PV features occurs from May to July (Figs. 7a,c). Finally, the spread of the 15 curves is generally quite large, indicating a significant year-to-year variability.

The pronounced interannual variability (up to a factor of 2) and seasonal cycles are similar on 320 K. The frequency of the stratospheric features has a clear summer maximum (similar to 350 K) whereas the frequency of tropospheric streamers and cutoffs peaks in winter. Note that the 320-K isentrope intersects the tropopause at about 65°N during summer and near 40°N during winter, and therefore different dynamical processes may be captured on this isentrope during the year.

To eliminate the influence of changes in the location of the isentropes, a vertically averaged seasonal cycle has been computed, taking into account all isentropes that intersect the 2-PVU tropopause between 30° and 80°N (Figs. 7i–l) in the zonal mean. The result is striking: for all PV features, the amplitudes of both the seasonal cycle and the interannual variability are strongly reduced compared to those on individual isentropes. The most frequent are stratospheric streamers (they cover on average about 1.2% of the Northern Hemisphere), stratospheric cutoffs occur with an average frequency of about 0.9% (with a small summer peak), and the least frequent are tropospheric streamers and cutoffs (about 0.7%).

It is an important conclusion that PV features near the extratropical tropopause reveal a significant seasonal cycle if considered on selected isentropes. However, this is mainly due to a seasonal shift in the position and tropopause intersection of the isentropes. The vertically and hemispherically integrated frequency of PV streamers and cutoffs is remarkably constant throughout the year.

b. Summary distributions

Figure 8 provides summary plots of the PV features’ distribution as a function of potential temperature and time of the year. The shading gives a relative measure of when and on what isentrope streamers and cutoffs occur (scaling is such that maximum values are equal to 1). For instance, in agreement with Fig. 7e, strato-
Spheric streamers (Fig. 8a) on 320 K occur most frequently in early summer, whereas on 350 K their maximum is shifted to late summer. Figures 8a–d show a domain with zero frequencies on lower isentropes. This domain is largest in summer and corresponds to the isentropes that do not intersect the tropopause.

Also shown in this figure is the seasonal cycle of zonal mean tropopause potential temperature at given latitudes, from 30° to 80°N (solid black lines). For instance, the contour line labeled 50°N indicates that in a zonal mean sense at this latitude the tropopause is intersected by the 310-K isentrope in January and by the 330-K isentrope in July and August. It turns out that the seasonal cycles of the frequency of streamers and cutoffs that appear rather involved if regarded on isentropes become much simpler if regarded along these contours of zonal mean tropopause potential temperature. Stratospheric streamers (Fig. 8a) occur most frequently on isentropes that intersect the tropopause near 60°N, with almost constant amplitude throughout the year. The frequency decays rapidly on lower isentropes, and on higher isentropes (and therefore farther equatorward) there appears a clear late summer maximum. A similar pattern (weak seasonal cycle on isentropes that intersect the tropopause in northern mid-latitudes and strong seasonal cycle on higher isen-

Figure 7. Time series of the percentage of hemispheric area covered by (a), (e), (i) stratospheric streamers, (b), (f), (j) tropospheric streamers, (c), (g), (k) stratospheric cutoffs, and (d), (h), (l) tropospheric cutoffs on (a)–(d) 350 K, (e)–(h) 320 K, and (i)–(l) the average over all levels that intersect the zonal mean tropopause between 30° and 80°N. The curves correspond to the individual 15 yr.
tropes) is found for all PV features. This indicates (in a zonal mean sense) a relatively constant behavior of Rossby waves in midlatitudes and enhanced seasonal variability in the subtropics. However, if the geographical patterns are also taken into consideration, then the seasonal changes are also significant in midlatitudes, as discussed in section 3.

Two final remarks about Fig. 8 concern the behavior on the lowest and highest isentropes considered. The winter maximum of stratospheric cutoffs on 295–300 K is most certainly a methodological artifact (orographically produced PV anomalies are misinterpreted as stratospheric cutoffs, as discussed previously in section 2b). On levels above 350 K, all PV features occur with high frequency. On these isentropes we cannot exclude the possibility that the ERA-15 data contain spurious subtropical PV structures. A preliminary comparison between ERA-15 and the 40-yr ECMWF Re-Analysis (ERA-40) PV features on 360 K for a single month (Wernli 2004) revealed significantly larger frequencies of stratospheric cutoffs in the ERA-15 dataset. This might be a consequence of the differing data assimilation technique (optimum interpolation in ERA-15 versus variational analysis in ERA-40) that affects in particular the data-sparse (sub)tropical regions. It should also be noted that the same comparison revealed excellent agreement on 320 K, highlighting the consistency of the two datasets near the tropopause in midlatitudes.

5. Link between PV features

So far, the four types of PV features have been discussed separately. However, as mentioned during the
Table 1. Statistical evaluation on 320 K for the entire ERA-15 time period of the frequency (%) of simultaneous links between different PV features. The row of an entry indicates which type of PV structure has been identified (at $t = 0$) and the column indicates the type of PV structure that has been linked to it (also at $t = 0$).

<table>
<thead>
<tr>
<th>If at $t = 0$ . . . then at $t = 0$</th>
<th>Tropospheric cutoff</th>
<th>Tropospheric streamer</th>
<th>Stratospheric cutoff</th>
<th>Stratospheric streamer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropospheric cutoff</td>
<td>100.0</td>
<td>4.1</td>
<td>1.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Tropospheric streamer</td>
<td>12.2</td>
<td>100.0</td>
<td>10.3</td>
<td>65.2</td>
</tr>
<tr>
<td>Stratospheric cutoff</td>
<td>1.8</td>
<td>4.4</td>
<td>100.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Stratospheric streamer</td>
<td>10.0</td>
<td>50.4</td>
<td>11.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

In Table 1, the percentages are shown for links without time lag on 320 K for the entire 15-yr time period. By definition the diagonal elements are 100%. The next largest values are 65.2% for stratospheric streamers to be found in the vicinity of tropospheric streamers and 50.4% for the reversed link. These high percentages confirm the impression from the case analysis (Figs. 2 and 3) that the two types of streamers very likely occur in pairs. Stratospheric cutoffs are found in the vicinity of stratospheric streamers (and tropospheric cutoffs near tropospheric streamers) with a frequency slightly larger than 10%. This type of link occurs probably after a partial streamer breakup that produces a tip vortex and a shortened streamer or before the merging of a cutoff with a streamer. Also with a frequency of about 10%, streamers of one type are linked with cutoffs of the other type. This is regarded as a variant of the frequent co-occurrence of tropospheric and stratospheric streamers.

Discussion of Figs. 2 and 3, the four categories are not physically independent. Cutoffs typically form through the breakup of streamers, and the two types of streamers sometimes occur in pairs. In the following, this aspect of a spatiotemporal link between PV streamers and cutoffs is examined in a statistical way. This is done by investigating individual PV features and their environment. For instance, for every stratospheric streamer identified on a certain isentrope, it is checked whether there is another PV feature in its vicinity, simultaneously or 6 h later. A spherical distance measure is used to define “vicinity”: if at least one grid point belonging to a second feature can be found within a 300-km-wide boundary around the first one, then the two features are regarded as “linked”; otherwise, they are not. Note that this search procedure takes into account the exact shape of the PV features. The threshold value of 300 km is somehow arbitrary; it is regarded as the reasonable distance to ensure a dynamical relationship between the linked features (RWB leading simultaneously to stratospheric and tropospheric streamers, streamers breaking up into cutoffs, cutoffs rejoining with streamers, etc.).

Table 2 summarizes the frequencies of links for the 320-K isentrope and a time lag of 6 h. First, for all four types of PV features there is a probability of 52%–63% that a feature of the same category can be found 6 h later in the vicinity as defined above (diagonal elements in the table). This indicates that more than half of the PV streamers and cutoffs persist for longer than 6 h. This simple approach might miss features that move fast and are located outside of the considered domain 6 h later. (A full tracking algorithm would be required to determine the lifetime of the individual PV features—this, however, is beyond the scope of the present analysis.) High frequencies are also found for tropospheric cutoffs occurring in the vicinity of tropospheric streamers 6 h later (32.2%) and for stratospheric cutoffs following stratospheric streamers (22.4%). This fits well with the conception of streamers breaking up into cutoffs. Obviously, tropospheric streamers break up even more frequently than their stratospheric counterparts (at least on 320 K). The reverse link (cutoffs leading to streamers of the same type) is less frequent but still
amounts to about 10%. This kind of link occurs when cutoffs get captured by their reservoir of origin in such a way that the joint structure is identified as a streamer. Still relatively large is the link between the two types of streamers (35%–45% with a time lag of 6 h compared to 50%–65% simultaneously; cf. Table 1) and between streamers and cutoffs of the other type (16%–20% here compared to about 10% simultaneously). This indicates the relatively high persistence of pairwise occurring RWB events of the two types. Finally it is noted that the total nondiagonal link percentages in Table 2 amount to about 80% for streamers and 20% for cutoffs, indicating again that cutoffs typically occur as solitary PV features.

The same analysis has also been performed on 300, 340, and 360 K, and the general picture is very similar to the one presented for the 320-K isentrope. From this statistical point of view, no remarkable difference occurs in the behavior of the four types of PV features on different isentropes.

6. Discussion and further remarks

In this study a novel approach has been introduced to identify PV streamers and cutoffs near the extratropical tropopause, and a climatology has been presented of their seasonal frequency distributions on different isentropic surfaces. Here the limitations of the methodology and dataset and the relationship to other climatologies are briefly discussed, and an outlook is given on possible extensions and applications of this study.

The technique, which is based upon a contour searching algorithm, provides a flexible tool to study the topology of near-tropopause PV features. Here, the adjustable parameters \( D \) and \( L \) have been chosen such as to identify filamentary structures that are not too small in size. Different parameter settings could, for instance, focus on small filaments (smaller values for \( D \) and \( L \)) or on broader-scale troughs and ridges (larger value for \( D \)). The examples shown in Figs. 2 and 3 indicated that the technique works successfully and that the specified values for \( D \) and \( L \) lead to the identification of filamentary structures that are very similar to the PV streamers detected and characterized in earlier studies (e.g., Appenzeller et al. 1996; Massacand et al. 1998). Slightly different values of \( D \) and \( L \) would obviously lead to a different number of identified PV structures; however, they would not affect the main results presented in this study (geographical distributions of stratospheric and tropospheric PV features and their annual cycle). Clear limitations occur on isentropes that intersect the surface topography. On such isentropes, frictional processes can lead to the generation of PV anomalies that, from inspection of the PV structure alone, cannot be distinguished from stratospheric PV cutoffs. As discussed in section 3b, some of the identified climatological maxima in the frequency of cutoffs on lower isentropes (e.g., near the Himalaya and over the Sahara) are most likely not of stratospheric origin. Here, either a Lagrangian investigation that determines the time history of the identified cutoff air parcels or a refined analysis of the three-dimensional PV field (as performed, e.g., by Sprenger et al. (2003) in order to identify tropopause folds) would be required to unambiguously separate stratospheric from diabatically and frictionally produced PV anomalies. Both these approaches are rather elaborate and have not been performed for the present study. Another limitation is due to the chosen ERA-15 dataset. As discussed at the end of section 4b, on higher isentropes, some near-tropopause PV structures do not appear to be fully consistent (loops of PV on 360 K, e.g., show high temporal variability and not the same degree of spatial consistency as revealed by the PV evolution on lower isentropes). Taking the different limitations into consideration, the climatology presented in this study is most reliable on isentropes ranging from 320 to 350 K. In any case it should be kept in mind that the climatologies correspond to a reanalysis dataset that, albeit of high quality, still represents only an approximation to the real atmosphere.

Comparison with other climatologies of RWB yields a fairly good agreement. However, since most of the previous studies focused on single isentropes, the present study provides a more complete picture of the overall RWB activity near the extratropical tropopause. Postel and Hitchman (1999) and Abatzoglou and Magnusdottir (2004) investigated RWB on 350 K and found a pronounced maximum during the summer season, in agreement with the results shown in Fig. 7a. Geographically, RWB was detected most frequently near the date line and about 60°W, very similar to our summertime streamer distribution (Fig. 6d). Note that their RWB identification method and the use of fairly coarse-scale PV fields focus on relatively large and strongly tilted streamers. The similarity of the results indicates that this type of stratospheric PV streamer also dominates our climatology. Waugh and Polvani (2000) considered the special category of stratospheric PV streamers on 350 K that reach deep into the Tropics (tip of streamer equatorward of 10° latitude). In contrast to the overall climatology presented by Postel and Hitchman (1999), they found maximum frequency of these deep streamers in winter, mainly over the Pacific (180°–260°E) and the Atlantic (20°–50°W). These regions of maximum southward penetration of strato-
spheric streamers compare well with the pattern shown in Fig. 4f. However, in our climatology, stratospheric PV streamers that reach 10°N are very rare (~1% southeast of Hawaii). The agreement with the results shown by Morgenstern and Carver (1999) is less good, in particular in the North Pacific region where they found maximum RWB on 330 and 350 K in the western and central part in contrast to the maximum in the eastern Pacific shown in Figs. 4d,f. This might be due to the different time periods considered (2 winter months versus a 15-winter average) and to the differing streamer definitions and identification techniques. For tropospheric streamers, Peters and Waugh (1996) identified the eastern North Atlantic and North Pacific as the preferred regions for their occurrence. This is confirmed by the present winter climatologies on 320–350 K (Figs. 4c–f). However, during summer the patterns vary significantly with potential temperature and, for instance on 350 K, the maxima are located more in the western/central parts of the Northern Hemisphere oceans (Fig. 6d). Finally, it is noteworthy that on 330 K the distribution of PV streamers (Fig. 4d) resembles the PV error climatology of the ECMWF model as presented by Dirren et al. (2003). This indicates that short-term forecast errors in the upper-level PV field are frequently associated with RWB.

The results presented in this study lead to exciting new questions, and because of the detailed identification of individual events (including their location, size, and orientation) they offer the possibility for an in-depth analysis of the relationship between RWB events and other meteorological processes and phenomena. For instance, it is now possible to determine in a statistically robust sense the importance of PV streamers and cutoffs for stratosphere–troposphere exchange. Such an event-based analysis is performed in a companion paper (Sprenger et al. 2007). Similarly, it would be possible to examine the link between PV streamers and cyclone life cycles. From the climatological distributions it appears that stratospheric streamers and cutoffs on 300–320 K (Figs. 4a–c, 5a–c) do not occur frequently in the key areas of North Atlantic and North Pacific cyclogenesis (see, e.g., Fig. 6a in Wernli and Schwierz 2006). It can be speculated that these PV structures therefore do not play an important role for cyclogenesis. However, for instance for Mediterranean cyclones, genesis occurs typically in a region with a high cutoff frequency on 310 K (Fig. 5b). A detailed event-based investigation would be required to address such questions. Another potentially related issue is the dynamical relationship between RWB and upper-tropospheric jet streams (see Koch et al. 2006 for a recent climatology). During winter, the North Pacific streamer maximum shown in Fig. 4 typically occurs in a region between the exit of the Pacific and the entrance of the North American jet stream (see Fig. 4a in Koch et al.). In contrast, the North Atlantic streamer maximum is located in a region with a frequently northward spiraling Atlantic jet stream to the north and the subtropical jet stream maximum over northern Africa to the south. Peters and Waugh (2003) investigated such settings (jet stream gap versus double jet structure) in an idealized context and found a different behavior with respect to the relative frequency of poleward and equatorward wave breaking. It is also rewarding to analyze the PV streamers’ shape in order to quantify the relative importance of the archetypal wave breaking configurations in different areas of the globe (Martius et al. 2007). Also, the application of the algorithm to the extended ERA-40 dataset will allow the performance of analyses of long-term trends and interannual variability.

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REFERENCES


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