The three-dimensional life ~~cycle~~ cycles of potential vorticity cutoffs: A global ERA-interim climatology (~~1979-2017~~1979-2018)

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Abstract. The aim of this study is to explore the nature of potential vorticity (PV) cutoff life cycles. While climatological frequencies of such ~~upper-level~~ near-tropopause cyclonic vortices are well known, their life cycle and in particular their three-dimensional evolution is poorly understood. To address this gap, a novel method is introduced that ~~allows tracking~~ uses isentropic air parcel trajectories to track PV cutoffs as three-dimensional objects. ~~As it is based on isentropic air parcel trajectories, the detailed evolution of the cutoffs~~ With this method, we can distinguish the two fundamentally different PV cutoff lysis scenarios on isentropic surfaces~~, including their associated cross-tropopause mass fluxes, can be analyzed. The novel~~ : complete diabatic decay vs. reabsorption by the stratospheric reservoir. This method is applied to the ERA-interim dataset ~~for the years 1979-2017~~ (1979-2018) and the first global climatology of PV cutoffs is presented that is independent of the selection of a vertical level and identifies and tracks PV cutoffs as ~~three-dimensonal~~ three-dimensional features. More than ~~40'~~150'000 PV cutoff life cycles are identified and analyzed~~in the almost 40-year data set. Known~~. The climatology confirms known frequency maxima of PV cutoffs ~~are confirmed and , additionally,~~ and identifies additional bands in subtropical areas in the summer hemispheres and a circumpolar band around Antarctica~~are identified. A detailed investigation of PV cutoff life cycles in different genesis regions reveals that PV cutoff genesis occurs as a result of distinct~~. The first climatological analysis of diabatic decay and reabsorption shows that both scenarios occur equally frequently – in contrast to the prevailing opinion that diabatic decay dominates. Then, PV cutoffs are classified according to their position relative to jet streams [equatorward (Type I), between two jets (Type II), and poleward (Type III)]. A composite analysis shows distinct dynamical scenarios for the genesis of the three types. Type I forms due to anticyclonic Rossby wave breaking ~~scenarios. In addition, there is a remarkable regional variability of PV cutoff mobility, lifetimes and vertical evolution. This regional variability of PV cutoff behaviour can to some extent be explained by differences in cross-tropopause mass fluxes and the varying frequencies of different lysis scenarios on isentropic surfaces, i. e. diabatic decay and reabsorption to~~ above subtropical surface anticyclones and hardly results in precipitation. Type II results from anticyclonic Rossby wave breaking in mid-latitudes in regions with split-jet conditions and is frequently accompanied by surface cyclogenesis and substantial precipitation. Type III cutoffs preferentially form due to cyclonic Rossby wave breaking within extratropical cyclones in the ~~stratospheric reservoir. It is found that, on a global average, reabsorption occurs about as frequently as~~ storm track regions. We show that important track characteristics (speed, travel distance, frequency of decay and reabsorption, isentropic levels) differ between the categories, while lifetime is similar in all categories. Finally, twelve PV cutoff genesis regions in DJF and JJA are selected to study the regional characteristics of PV cutoff life cycles. As a particularly novel aspect, the vertical evolution of PV cutoffs along the life cycle is investigated.

We find that, climatologically, PV cutoffs reach their maximum vertical extent about one day after genesis in most regions. However, while in some regions PV cutoffs rapidly disappear at lower levels by diabatic decay, ~~but on higher isentropic levels. Further,~~ they can grow downward in other regions. In addition, regional differences in lifetimes, the frequencies of diabatic decay and reabsorption, and the link to surface cyclones are identified that cannot be explained only by the preferred regional occurrence of the ~~temporal link between PV cutoffs and associated surface cyclones is investigated. Novel insights are that (i) the frequency and characteristics of this link strongly depend on the region, and (ii) PV cutoffs are frequently~~ different cutoff types. Finally, we also show that in many regions PV cutoffs can be involved in surface cyclogenesis ~~a few days~~ even after their formation.~~PV cutoffs forming from similar Rossby wave breaking scenarios in different regions also show remarkable similarities in other characteristics~~

This study is an important step towards quantifying fundamental dynamical characteristics and the surface impacts of PV cutoffs. The proposed classification according to the jet-relative position provides a useful way to improve the conceptual understanding of ~~their life cycle. Based on that, a classification of~~ PV cutoff life cycles ~~into three types is proposed: Type I forms from anticyclonic Rossby wave breaking equatorward of the jet stream, Type II is the result of anticyclonic Rossby wave breaking followed by cyclonic Rossby wave breaking between the polar and the subtropical jets, and Type III forms from cyclonic wave breaking in the storm track regions . While diabatic decay is particularly frequent for Types I and II, reabsorption dominates for the Type III life cycle.~~ in different regions of the globe. However, these life cycles can be substantially modified by specific regional conditions.

1 Introduction

~~Meso-~~ Meso-scale to synoptic-scale intrusions of anomalously cold air masses with a closed cyclonic circulation in the mid and upper troposphere frequently occur in all extratropical regions. In the subtropics and ~~mid-latitudes~~midlatitudes, these upper-level closed cyclones often form when air from the poleward side of the jet stream is transported far equatorward, forming an elongated cold-air tongue. Subsequently, the tongue breaks up into one or more upper-level cyclonic vortices separated from the main polar reservoir (**?**), which are usually located equatorward of the jet stream and isolated from the main westerly flow. This process is known as Rossby wave breaking (RWB, **?**) and the resulting upper-level cyclonic systems, which are often termed cutoff lows (COLs), have been first characterized comprehensively by **?**. There are two archetypes of RWB: Anticyclonic RWB occurs on the anticyclonic shear side, i.e., equatorward, of the jet stream and cyclonic RWB on the cyclonic shear side, i.e., poleward, of the jet stream (**???**). In the past, both types but in particular anticyclonic RWB have been linked to the formation of COLs (**??**).

Several approaches exist to identify COLs. Classically, they are identified as closed geopotential height contours in the mid or upper troposphere (e.g., **???**). COLs are also associated with an anomalously low tropopause, i.e., with stratospheric air in regions that are climatologically tropospheric. Stratospheric air masses exhibit high values of potential vortictiy (PV), typically exceeding $2\,\mathrm{PVU}$ [1 PVU = $10^{-6}\mathrm{m^{-2}s^{-1}K\,kg^{-1}}$], whereas tropospheric air masses typically have PV values below $2\,\mathrm{PVU}$. Therefore, PV is a useful quantity to identify COLs and to describe their behavior (e.g., **????**). and results in similar climatological frequency patterns as the classical COL identification based on geopotential height (?). In the PV framework, COLs are usually identified ~~as closed~~ regions with PV values larger than 2 PVU on an isentropic surface~~. They~~ , that are isolated from the main stratospheric high-PV reservoir~~, and~~ . They are also termed stratospheric PV cutoffs [for brevity hereafter PV cutoffs]. PV cutoffs are inherently the same phenomenon as COLs, as illustrated in a case study by **?**. But COLs have classically been regarded as upper-level closed cyclones equatorward of the jet stream, following the picture of **?**, whereas the concept of PV cutoffs extends towards the pole, as long as a stratospheric reservoir can be meaningfully defined and separated from the PV cutoff on the considered isentropic level.

Many studies show the high relevance of PV cutoffs for surface weather in specific regions, in particular the formation of (intense) surface cyclones and heavy precipitation events. For example, **?** found that more than a third of the Meditarranean COLs are associated with a surface cyclone. In case studies, PV cutoffs have been reported to be dynamical key elements for the intensification of a subtropical cyclone in the South Atlantic (**?**) and the genesis of strong Mediterranean cyclones (**?**). COLs accompany suptropical cyclones in most of the cases in the southwestern South Atlantic (**?**) and the eastern North Atlantic (**?**), where they frequently influence the occurrence of tropical transition (**?**). The work of **?** indicated that PV cutoffs can also lead to the genesis of polar lows. Furthermore, they significantly contribute to (extreme) precipitation in the Mediterranean region (**??**), the Alps (**?**), the Great Plains and western United States (**??**), ~~Northeast~~ northeastern China (**?**), South Africa (**?**), southeastern Australia (**?**), and Iraq (**?**). More specifically, they can play a key role in triggering heavy convective storms by favoring the release of conditional instability via destabilization and dynamical forcing (e.g., **??**). They can also act as "moisture collectors" (**?**) if they remain quasi-stationary and repeatedly advect warm and moist air towards a region where it is forced to ascend, i.e., a baroclinic zone or high orography (e.g., **????**).

The life ~~cycle~~ cycles of PV cutoffs ~~is~~ are strongly governed by diabatic processes. The latent heating associated with cloud formation in the vicinity of PV cutoffs, likely together with turbulent mixing, can modify their evolution and eventually lead to their rapid diabatic decay, resulting in irreversible mixing of stratospheric air into the troposphere (e.g., **?????**), so-called stratosphere-to-troposphere transport (STT). **?** showed that PV cutoffs can also diabatically grow and intensify, likely due to radiative cooling at cloud tops or humidity gradients at the tropopause, potentially leading to troposphere-to-stratosphere transport (TST). Previous studies (e.g., **?**) have shown that PV cutoffs are often associated with both STT and TST, with STT being 2-3 times larger on average. The modification of PV cutoffs by diabatic processes can strongly depend on the considered isentropic level. This indicates that PV cutoffs are potentially complex three-dimensional features, that can intensify on a higher isentropic level and at the same time decay on a lower isentropic level (**?**). In addition, as already stated by **?**, instead of diabatically decaying, a PV cutoff "*(...) could of course be removed by simply being advected back along isentropic surfaces into the polar stratospheric reservoir*" (a process we call "reabsorption"), but that "*synoptic experience suggests that the chances of this happening in less than a week are small*". Later studies did not pick up this topic and therefore a quantitative estimation of the relative frequencies of diabatic decay and reabsorption is ~~still~~ missing.

Due to the large variety of near-tropopause cyclonic vortices on the globe, there is no clear consensus in the scientific literature which vortices are to be considered COLs. While many studies focused on COLs located equatorward of the jet stream, others showed that there exist mid- and upper-level closed cyclones poleward of the jet stream, e.g., over the Hudson Bay, south of Greenland, and the North Pacific (**?????**). **?** provided the first climatology of COLs that covers both hemispheres (albeit restricted to the mid-latitudes) and captured the classical COLs at lower latitudes but also COLs at higher latitudes by considering two pressure levels (200 hPa and 500 hPa). Focusing on similar systems in polar regions, **?** investigated positive PV anomalies in the lowermost stratosphere and **?** local minima of tropopause-level potential temperature, which are sometimes termed tropopause polar vortices (TPV, **?**). However, there is no study so far that includes all near-tropopause cyclonic vortices, independent of their latitude.

The frequencies, geographical distribution, seasonality, and tracks of the “classical” COLs equatorward of the jet stream are well known in both hemispheres. Hotspots in the Northern Hemisphere are the eastern North Pacific, eastern North Atlantic and the Mediterranean, and northern China-Siberia (**???**). In the Southern Hemisphere, they tend to occur around the main land masses, i.e., South America, South Africa, and Australia / New Zealand (**???**). Most COLs have lifetimes of 2-3 days and generally travel eastward. Some studies suggested that they are very mobile and travel hundreds of kilometers (**???**) whereas others point out their quasi-stationarity (**??**). ~~The first climatology of PV cutoffs was presented by **?**. **?** showed that the geographical distribution of COLs at 200 hPa and PV cutoffs generally agree well, if PV cutoffs are identified at the appropriate isentropic level, depending on the season and region. However, **?** showed that also climatologies of COLs strongly depend on the considered pressure level. While many studies focused on COLs located equatorward of the jet stream, others showed that there exist mid-~~ A few regional studies have also investigated the vertical evolution of COLs and ~~upper-level closed cyclones poleward of the jet stream,~~ the extension of their circulation to the surface (e.g.~~over the Hudson Bay, south of Greenland, and the northern Pacific (**?????**). **?** provided the first climatology of COLs that covers both hemispheres (albeit restricted to the mid-latitudes) and captured the classical COLs at lower latitudes but also COLs at higher latitudes by considering two pressure levels (200 hPa and 500 hPa). Focusing on similar systems in polar regions, **?** investigated positive PV anomalies in the lowermost stratosphere and **?** local minima of tropopause-level potential temperature, which are sometimes termed tropopause polar vortices (TPV, **?**)~~, **??**). A main result from these studies is that more intense COLs tend to have a deeper vertical structure and a higher precipitation intensity. However it is yet unknown if and how all these characteristics of COLs vary across regions. **?** emphasized this by noting that its is unclear how the results they find for subtropical COLs in the Southern Hemisphere relate to COLs in other regions. A major obstacle to comparing PV cutoffs across regions and hemispheres are the wide ranges of different identification and tracking methods used in existing regional studies. Furthermore, climatological frequencies of PV cutoffs and COLs strongly depend on the selected isentrope or pressure level (**??**).

Their relevance for surface cyclones, precipitation, and STT in many regions on the globe explains the high research interest in PV cutoffs in the last three decades. However, despite the large number of climatological studies, a ~~global quantitative analysis of their importance for these aspects is lacking~~study that includes life cycles of all PV cutoffs, independent of their latitude and vertical level is missing. This, however, is an important basis to comprehensively characterize PV cutoff life cycles and how they differ across regions, as well as to quantify their importance for surface weather. Also, a climatological perspective on their ~~three-dimensional life cycles and their modification~~ vertical evolution and how it is modified by diabatic processes, including the frequencies of decay and reabsorption, is missing. ~~A reason for this is that current climatologies are restricted by and strongly depend on the selection of a vertical level. Also, they are not global and many focus on features equatorward~~

~~of the jet stream only.~~ This study aims to compile a climatology of PV cutoffs that fills these knowledge gaps and provides a basis for a comprehensive global analysis of PV cutoff life cycles~~, their diabatic modification, and their surface impacts~~. While COLs have been tracked previously, ~~the climatology presented in~~ this study is the first that explicitly tracks PV cutoffs. For the tracking, a novel method is introduced that is based on air parcel trajectories and allows quantifying ~~cross-tropopause mass fluxes~~how many PV cutoffs decay diabatically and how many are reabsorbed.

The identification and tracking of PV cutoffs is introduced in detail in Sect. **??**. In Sect. ~~**??**~~**??**, a global climatological overview of PV cutoff ~~frequencies, their genesisand lysis~~occurrence, genesis, lysis, and decay and reabsorption is presented. ~~This is followed by a comprehensive analysis of various novel~~ Further, PV cutoffs are classified into three types according to their jet-relative position and various aspects of their life ~~cycle in Sect. **??**~~cycles are compared and contrasted. Section **??** presents comprehensive regional analyses of PV cutoff life cycles with genesis in specific geographical regions. Section **??** ~~discusses links to the literature,~~ summarizes the main conclusions and provides an outlook for further research topics that could be addressed with this climatological dataset of PV cutoffs.

2 Data and Methods

2.1 Data

All analyses in this study are based on the ~~ERA-interim~~ ERA-Interim dataset (**?**) for the years ~~1979-2017~~1979-2018. Data are available every 6 h on 60 vertical levels and have been interpolated from T255 spectral resolution to a regular grid with a horizontal resolution of 1°. PV is computed from the primary ERA-interim variables. Horizontal winds and PV are interpolated onto a stack of isentropic levels from ~~290-350~~275-360 K with a 5 K interval. For the same time period, ~~masks of stratospheric and tropospheric PV streamers based on the method of **?**, and of cyclones~~upper-level jet streams, identified according to **?**, and surface cyclones, identified and tracked according to **?**, are retrieved from the dataset described by **?**.

2.2 PV cutoff identification

The PV perspective is adopted in this study because it offers several advantages to identify and track COLs compared to other approaches. First, the identification of PV cutoffs as closed 2 PVU contours on isentropic surfaces is unambiguous, conceptually simple, in principle does not require additional criteria or variables [as for example the methods by **?** and **?**], does not depend on the hemisphere considered [as the approach by **?**], and therefore strongly reduces the methodological sensitivity [as exists for COL identification, see **?**]. Second, the invertibilty principle of PV allows for a very intuitive interpretation of the effect of PV cutoffs on the surrounding atmosphere (**?**). And third, PV is, in the first order, conserved on isentropic surfaces, which means that (i) the movement of PV cutoffs is quasi-adiabatic rendering a tracking on isentropic surfaces comparably straightforward, and (ii) deviations from the adiabatic advection of the PV cutoff are indicators of diabatic processes. However, as for any other previously used approach, the restriction of the identification to single levels would neglect the fact that PV cutoffs are often highly three-dimensional features. Therefore, in this study, PV cutoffs are identified and tracked as three-dimensional objects within a stack of isentropic levels from ~~290-350~~275-360 K in 5 K intervals, extending the approach by **?**. This method allows us to investigate PV cutoffs in the subtropics, where they ~~are most frequent on isentropic levels around 330-350~~occur on isentropes around 330-360 K (**?**), the mid-latitudes (310-330 K), and ~~polar regions (290-310~~at high latitudes (275-310 K). ~~Note that with this choice of levels~~ It is important to note that for the tracking, only the range 275-350 K is used in order to avoid PV cutoffs in the deep tropics that occur above 355 K [Fig. 8b in **?** and consistent with the PV streamers found by **?**]. The upper bound of 360 K for the identification of ~~features close to the pole is limited, as there some features occur on even lower isentropic levels, in particular in winter. The tropopause in TPVs over the Canadian Arctic, for example, reaches isentropic levels below 280~~PV cutoffs used here allows to take into account the full vertical extent of subtropical PV cutoffs that can be tracked on 350 ~~K (?).~~ K or below but extend higher up. The tropical PV cutoffs are excluded because of two reasons. On the one hand, a much higher upper bound would be required to fully capture them, rendering data handling and analysis tedious. On the other hand, including a satisfactory discussion of these so far under-researched systems would go beyond the scope of this paper.

Our identification of PV cutoffs starts on single isentropic levels, essentially using the algorithm by **?** with the modification that, here, the stratospheric reservoir does not necessarily have to encompass the pole, but is defined as the largest area bounded by a closed 2 PVU contour on each isentrope. This becomes particularly relevant at lower isentropic levels and towards the pole, because there the size of the stratospheric reservoir decreases and often does not encompass the pole. The method of **?** has the major drawback that it identifies also features with PV larger than 2 PVU produced by diabatic processes (e.g., within extratropical cyclones) or frictional forces near high topography, i.e., features that are not of stratospheric origin. Therefore, the labeling algorithm of **?** is used here, which assigns to each grid point a label that classifies it as stratospheric if it is three-dimensionally connected to the stratospheric reservoir and if it has a specific humidity of less than 0.1 $\mathrm{g\,kg^{-1}}$. This label can be used do separate true PV cutoffs from diabatically produced PV features. Then, the PV cutoffs on the different isentropic levels are clustered if they overlap with each other and hence form a three-dimensional PV cutoff. Finally, PV cutoffs larger than $5 \cdot 10^6\,\mathrm{km}^2$ (about half the area of the US) at a certain isentropic level are removed from that level to avoid the identification of very large PV cutoffs, which often occur on higher isentropic levels. The resulting three-dimensional PV cutoffs are in the following referred to as PV cutoff objects.

2.3 Lagrangian PV cutoff tracking

The tracking takes advantage of the material conservation of PV, i.e., the quasi-adiabatic movement of PV cutoffs. There are some similarities to the tracking developed by **?** to track PV anomalies in the lowermost stratosphere, which is based on advection of the PV anomalies by the isentropic wind. But the tracking presented in this study uses isentropic air parcel trajectories started from each grid point within the PV cutoff and calculated foreward for 6 hours. The final positions of these short trajectories can be regarded as "adiabatic forecast" of the PV cutoff six hours later, and it serves to accurately track the cutoff in time as well as to identify diabatic decay and reabsorption. In addition, the deviation of the observed evolution from this adiabatic forecast can be used to quantify cross-tropopause transport. This method to quantify cross-tropopause mass fluxes is conceptually similar to the approach by **?**. Note that, in this study, this Lagrangian PV cutoff tracking is used to obtain PV cutoff tracks and to identify decay and reabsorption. For a discussion of cross-tropopause mass fluxes the reader is referred to **?**. As another advantage compared to previous methods of COL tracking, the trajectory-based approach also works in regions with strong advection, for example near the jet stream ~~, when~~ where consecutive features do not always overlap spatially. The tracking connects PV cutoff objects to non-branching tracks, i.e., without merging and splitting, and consists first of tracking on isentropic surfaces, and second, a connection of isentropic tracks to 3D tracks. These two steps are illustrated in Figs. **??** and **??**, respectively, and are now discussed in detail.

2.3.1 Tracking on isentropic surfaces

A 3D PV cutoff object consists of one or more 2D PV cutoffs, one on each isentropic level from 275-360 K. The 2D PV cutoffs at a given time t_0 are referred to as *parents* (grey features in Fig. **??**). Isentropic tracks are constructed forward in time, by allowing only one successor per track (subsequently referred to as *child*, green features labeled accordingly in Fig. **??**a-d), i.e., in the case of a splitting of a PV cutoff, the smaller part is ignored. This substantially eases the analysis of the tracks. From each *parent*, 6-hourly isentropic forward trajectories are started from each grid point (black crosses in Fig. **??**), using the Lagrangian analysis tool Lagranto (**??**). A 2D PV cutoff at time t_0+6 h is a potential *child* if it inherits at least one air parcel from the considered *parent*. In the following, a variety of situations is considered that may occur during this step.

In the most simple situation, the movement of the 2D PV cutoff during this time interval is perfectly adiabatic (Fig. **??**a) and all trajectories arrive within a 2D PV cutoff (the *child*) at the same level at time t_0+6 h (blue crosses in Fig. **??**a). In a situation with diabatic activity (Fig. **??**b), the adiabatic forecast of the PV cutoff (blue and red crosses in Fig. **??**b) may deviate from reality at time t_0+6 h (~~blue and orange crosses /~~ the green feature in Fig. **??**b). In this case, some trajectories end up outside of the *child* (red crosses in Fig. **??**b), showing that the 2D PV cutoff shrinks due to STT. Also, the 2D PV cutoff may grow due to TST (orange cross in Fig. **??**b). ~~Note that, as a limitation of this step, orange grid points could also represent merging of stratospheric PV that detaches from the stratospheric reservoir with the PV cutoff and red grid points could be merging of PV cutoff air with the stratospheric reservoir. We assume that these events are relatively rare such that the resulting overestimation of STT and TST is small.~~ If, additionally to STT and TST, splitting occurs (Fig. **??**c), the 2D PV cutoff is selected as *child* that inherits most air parcels from the *parent* (lower green feature in Fig. **??**c). The trajectories arriving within the other 2D PV cutoff(s) at time t_0+6 h (blue-gray crosses and upper green feature in Fig. **??**c) are ~~counted~~ considered as shrinking due to splitting. It may also occur that two (or more) *parents* merge to one *child* (Fig. **??**d). In this case, the *child* is attributed to the *parent* (*parent 1* in Fig. **??**d) from which it inherits more air parcels (number of blue crosses vs. number of gray crosses). The trajectories that the *child* inherits from the other parent(s) (*parent 2* in Fig. **??**d) are counted as growth due to merging and the track ends for the other parent(s). If the track of a 2D PV cutoff does not end via merging to another 2D PV cutoff, it does so either via complete diabatic decay (Fig. **??**e), or (complete or partial) reabsorption to the stratospheric reservoir (Fig. **??**f). If all trajectories from the *parent* arrive in a region with PV<2 PVU (red crosses in Fig. **??**e), complete diabatic decay (involving STT) occurs. Air parcels arriving in a region with PV>2 PVU but not within a PV cutoff are counted as reabsorption (blue crosses in Fig. **??**f). In the case of merging, air parcels from the parent(s) for which the track ends (*parent 2* in Fig. **??**d) and that end up in the child are also considered as reabsorption. The two possibilites, reabsorption by the stratospheric reservoir and reabsorption by a larger cutoff, have relative frequencies of 89 % and 11%, respectively.

Once all parents at time t_0 have been considered, the same is repeated for the subsequent time interval. In this way, tracks are continued for all 2D PV cutoffs identified as *child* in the previous time step, and new tracks are initialized for all other 2D PV cutoffs.

2.3.2 Construction of 3D tracks

After isentropic tracks are constructed, PV cutoff objects are concatenated to tracks representing the three-dimensional evolution. The resulting 3D tracks consist of at least one isentropic track but can include a large number of isentropic tracks on different isentropic levels. Because we aim to avoid branching of tracks, a major challenge in this step is to reasonably handle situations during which two or several isentropic tracks of a single 3D track do not contain the same PV cutoff object at a given time instant. This can occur as a result of merging and splitting. Consider, for example, the splitting situation illustrated in Fig. **??**c. For the isentropic level shown, the isentropic track continues from the parent to the child and the lost child is dismissed. If, for example, such a splitting occurs simultaneously at another isentropic level where the PV cutoff labelled as “lost child” inherits more trajectories from the parent than the cutoff labelled as “child”, the two isentropic tracks are continued with a different PV cutoff object. Such a disagreement between tracks on different isentropic levels due to splitting is illustrated in Fig. **??** [see gray box with label c], where the track on 325 K is continued with a different PV cutoff object (red square) than on 310-320 K (blue dots). To create the non-branching 3D track, the following steps are required:

(i) *Identify overlapping tracks*: An isentropic track is selected and all isentropic tracks on all isentropes are identified that at least once overlap with the selected track (i.e., contain the same 3D PV cutoff object). This search is repeated for all overlapping tracks until no further tracks are found (see all lines independent of the color in Fig. **??**).

(ii) *Create non-branching 3D track from overlapping tracks*: The overlapping tracks are used to connect PV cutoff objects to a non-branching track according to the following rules: (a) The first time step a track of the overlapping tracks exists at any isentropic level marks the start of the 3D track. If there is more than one PV cutoff object at this time step that belongs to the overlapping tracks (which occurs if two tracks merge at a later time step), the dominant PV cutoff object is identified as the one with more isentropic levels or, if the number of levels is equal, the larger cutoff is selected [~~see red and~~ blue markers in the box (a) in Fig. **??**]; (b) Then, for the next time step, only PV cutoff objects are considered as successors if they are connected via an isentropic track with the previous PV cutoff object (~~see red and~~ blue markers in the box (b) in Fig. **??**). (c) If rule (b) has been applied and still more than one PV cutoff object is part of the overlapping tracks at a later time step (which occurs if isentropic tracks are continued differently on different isentropic levels) the same criteria (depth and size) are applied as in rule (a) to select the dominant cutoff [~~see red and~~ blue markers in the box (c) in Fig. **??**]. Eventually, tracks are only retained if they have a minimum lifetime of 24 h.

~~To focus on PV cutoffs that become dynamically relevant, i.e. potentially have a substantial effect on the static stability and wind field, they are required to extend over at least three isentropic levels at least once during their lifetime (i.e. reach an isentropic depth of at least 15 K). With this filtering, about 30% of the previously identified tracks are retained in both hemispheres. As a result, a~~ A total number of ~~46'353~~ 152'615 PV cutoff tracks provide the basis for this study, which is the largest dataset of PV cutoffs/COLs analyzed so far. On average, this amounts to ~~about 100~~ over 300 PV cutoffs per month. To visualize tracks and locate genesis and lysis events the PV cutoff centre is computed as the average of the coordinates of all grid points within the PV cutoff object weighted by their PV value. The area of the PV cutoff is determined as the area of the projection of the 3D PV cutoff onto a 2D plane, i.e., it includes all grid points that are part of the PV cutoff on at least one isentropic level. Examples demonstrating the application of the tracking to individual cases are shown in the supplementary material S3.

2.3.3 Limitations

The tracking method has two important limitations which are briefly mentioned here. First, only non-branching tracks are allowed and the decision criteria used may not represent the most reasonable track continuation in some cases. However merging and splitting are comparably rare. Therefore, this limitation does not question the usefulness of the method and the quality of the results presented here. At the poles, where ~~mass fluxes associated to~~ merging and splitting ~~are larger~~ occurs more frequently and the definition of PV cutoffs becomes less obvious, this limitation is strongest. Second, the tracking procedure requires the computation of a large number of trajectories and is therefore computationally expensive. This ~~limits its application~~ makes its application less straight forward to datasets much larger than ~~ERA-interim or to large~~ ERA-Interim or to operational ensemble forecasts for quasi real-time purposes.

2.4 ~~Computation~~ Classification of ~~mass fluxes~~PV cutoffs according to their position relative to the jet streams and the limited role of statistical significance testing

~~Diabatic processes can change PV of air parcels and thereby lead to a mass transport across the tropopause. In addition, quasi-adiabatic merging with another PV cutoff or injection of mass from the stratospheric reservoir can increase, and splitting can decrease,~~ In order to investigate whether different life cycle characteristics depend on the relative position of PV cutoffs to the ~~mass of a PV cutoff . With the Lagrangian tracking introduced in section **??**, these mass changes can be quantified. On a given isentropic level, the 6-hourly change of mass~~ jet streams, PV cutoffs are classified into three types: Type I (equatorward of the jet stream), Type II (between two jet streams), and Type III (poleward of the jet stream). Jet streams are identified according to **?** as regions where the vertically averaged wind speed between 100 and 400 hPa exceeds $30\,\mathrm{m\,s^{-1}}$. The jet-relative position of each PV cutoff is then determined as follows. All jet streams are identified that are intersected by the meridian through the PV cutoff center at genesis time. If jet streams are found only poleward of the PV cutoff, it is classified as Type I (22.4 % of all cutoffs). If jet streams are found poleward and equatorward of the PV cutoff~~due to TST, STT, merging, and splitting equals the number of grid points, i. e., trajectories, experiencing this process multiplied by the mass represented by the trajectories. This basic approach to quantify cross-tropopause transport using air parcel trajectories has been introduced by **?** and applied in various studies thereafter (e. g. **???**). The mass of a trajectory initiated at grid point i can be calculated from the pressure~~

~~thickness of the isentropic layer $\theta \pm 2.5\,\mathrm{K}$ at time t according to~~

$$M_\mathrm{i}(\theta,t) = \frac{1}{g}\cdot A_\mathrm{i}\cdot\left[p_\mathrm{i}(\theta-2.5\,\mathrm{K},t)-p_\mathrm{i}(\theta+2.5\,\mathrm{K},t)\right],$$

~~where A_i denotes the area represented by grid point i, $p_\mathrm{i}(\theta,t)$ the time- and level-dependent pressure at grid point i,~~ , it is classified as Type II (33.2 %), and ~~g the gravitational acceleration. To facilitate the computation, the mass averaged over all N grid points within aPV cutoff at isentropic level θ and time t is used as representative mass for these grid points at the level θ. It is computed as~~

$$M_\theta(t) = \frac{1}{N}\sum_{i=1}^{N} M_\mathrm{i}(\theta,t).$$

~~The mass flux due to a certain process (e.g. STT) can then be calculated for each PV cutoff at each time step of its life cycle as total mass transport over all levels divided by the cutoffarea $A(t)$~~

$$m_{STT}(t) = \frac{\sum_\theta n_\theta^{STT}(t) M_\theta(t)}{A(t)},$$

~~where $n_\theta^{STT}(t)$ is the number of trajectories experiencing STT on the isentropic level θ at time t. The division by the area yields a measure that is independent of the size of the PV cutoff and is therefore better comparable among different~~ if jet streams are found only equatorward of the PV cutoff, it is classified as Type III (39.4 %). Few PV cutoffs cannot be classified because jet streams are absent at the longitude of PV cutoff genesis (5 %). This is mostly the case in the Northern Hemisphere in summer. To draw statistically robust conclusions about observed differences between the three cutoff types (see Sect. **??**), statistical significance testing has to be applied. However, in our case (using the Wilcoxon-rank sum and Kolmogorov-Smirnov tests), the sample sizes are so large that basically all differences between composite means or empirical distributions turn out to be statistically significant, even if they are relatively small. Hence, we will focus on differences that are (a) sufficiently large and (b) can be reasonably explained with physical arguments.

2.5 Linking PV cutoffs and surface cyclones

To study the link between PV cutoffs and surface cyclones, all surface cyclones are identified that reach spatial proximity to a PV cutoff. Here, spatial proximity occurs if the distance between the centre of a surface cyclone and a PV cutoff is less than 600 km. Note that both, PV cutoffs and ~~to other studies. There are two major differences to the approach by **?** and subsequent trajectory-based quantifications of STT and TST. First, the minimum time required for an air parcel to stay at one side of the tropopause (so-called residence time) is 6 h while in other studies mostly residence times of one or several days have been used. As shown by **?**, the cross-tropopause mass flux decreases with increasing residence time τ according to a power law (τ^κ, $\kappa \approx -0.5$). Therefore, the values~~ surface cyclones, are required to have a minimum lifetime of one day in this study~~tend to be higher than in other studies (approximately 3 times higher compared to a 48 h residence time). Second, in order to enable a tracking of cutoffs on isentropes, this approach is based on isentropic trajectories instead of three-dimensional kinematic trajectories used in other studies.~~ .

3 ~~Climatology of PV cutoff frequencies, genesis, and lysis~~

3 Global climatology of PV cutoff life cycles

This section discusses a range of climatological aspects of PV cutoffs using the full global dataset. A comprehensive discussion of occurrence, genesis, and lysis frequencies is followed by the first climatological analysis of diabatic decay and reabsorption. Finally, PV cutoffs are separated into three categories, based on their relative position to the jet streams. For these categories, synoptic composites of PV cutoff genesis and the empirical distributions of various life cycle characteristics are analyzed.

3.1 Frequencies of occurrence, genesis, and lysis

~~This section provides a~~ First, a detailed global overview of PV cutoff occurrence and favoured genesis and lysis regions ~~.~~ is provided and related to the climatology of the zonal upper-level flow. Given that this study presents the most comprehensive climatology of PV cutoffs so far, such an in-depth discussion is justified. To this aim, Fig. **??** shows maps of seasonal mean PV cutoff frequencies for boreal winter (DJF), spring (MAM), summer (JJA), and autumn (SON). These frequencies indicate the percentage of time steps ~~at which~~ when a 3D PV cutoff is located at a particular grid point, independent ~~on~~ of the number of levels covered by the 3D PV cutoff. PV cutoff frequencies are ~~substantially~~ higher in the Northern Hemisphere (annual mean hemispheric average of ~~4.3~~5.8%) than in the Southern Hemisphere (~~2.1~~4.0%) in all seasons except DJF, when frequencies are ~~similar in both hemispheres~~about 1.2 percentage points larger in the Southern Hemisphere. Figure **??** shows a seasonal cycle with hemispheric averages about ~~two times larger in the summer season than in the winter season in both hemispheres~~thirty percent larger in summer than in winter in the Northern Hemisphere, and about two times larger in the Southern Hemisphere. The number of tracks ~~(not shown)~~ exhibits a much weaker seasonal cycle ~~with about 14% (27%)more cutoff tracks in JJA (SON) than in DJF in the Northern Hemisphere, and 53% more cutoff tracks in DJF than in JJA in the Southern Hemisphere,~~ (not shown), indicating that cutoffs in summer ~~are~~ tend to be longer-lived.

In DJF (Fig. **??**a), ~~the~~ there is a large northern hemispheric maximum over Southern Europe and the Mediterranean with frequencies up to 11%~~is conspicuous.~~. It coincides with the region of low upper-level zonal wind speeds (black lines in Fig. **??**a) downstream of the North Atlantic storm track, where anticyclonic RWB occurs frequently (**??**). Consistently, this frequency maximum is located poleward of the subtropical jet over northern Africa and equatorward of the North Atlantic jet stream. Note that, in Fig. **??**, we identify the climatological positions of the jet streams based on maxima of the mean zonal wind speed. Similarly, the frequency maximum over the southwestern US occurs in a region with frequent anticyclonic RWB downstream of the North Pacific storm track. Other frequency maxima in the Northern Hemisphere occur over ~~Newfoundland,~~ northeastern Canada and the western North Atlantic, as well as the Russian Far East and the North Pacific. Some of these high frequencies coincide with maxima of cyclonic RWB in the storm track regions (**??**), but the high frequencies over the Canadian Arctic and the ~~southwestern US, and near the Sea of Japan~~Russian Far East do not. However, they coincide with PV streamer maxima on 300 K (**?**). This indicates that PV cutoffs in these regions may frequently result from PV streamers without significant cyclonic or anticyclonic tilt. A comparison to **?** also suggests a link to the occurrence of TPVs in these regions. In the Southern Hemisphere, PV cutoff frequencies have a clear maximum in a large tilted band from the central subtropical South Pacific towards the southeast reaching southern South America. A similar band is also present over the South Atlantic, with two maxima east of Brazil and west of South Africa. High frequencies occur also in the southern Indian Ocean ~~,~~ and over New Zealand~~, and in~~. These maxima are located equatorward of the jet stream and coincide with maxima of anticyclonic RWB (**??**). Further, PV cutoffs are frequent poleward of the jet stream along a circumpolar band at 60°S around Antarctica, where cyclonic RWB is frequent (**??**).

In MAM (Fig. **??**b)~~.~~, PV cutoff frequencies ~~over Europe decrease and shift northward while they strongly~~ increase over the ~~North Pacific. Additional frequency maxima appear over the Canadian Arctic and central Russia. The appearance of these polar frequency maxima may also be due to generally lower altitudes of the isentropic levels in MAM compared to DJF. The 290 K lower bound used in this study may enable cutoff detection in MAM closer to the pole~~eastern parts of the North Atlantic and the North Pacific, as well as at high latitudes in the Northern Hemisphere. The frequencies in the Southern Hemisphere decrease in most regions and the circumpolar band shifts equatorward and becomes less ~~symmetric. The~~ uniform. The subtropical jet stream appears over Australia leading to split-jet conditions. A maximum appears over southern Australia, New Zealand and the South Pacific between the polar and the subtropical jet streams. The summer maxima east of Brazil and in the subtropical South Pacific ~~disappear and a new maximum appears over southeastern Australia reaching far into the South Pacific~~are absent in MAM.

In JJA (Fig. **??**c), frequencies ~~over the Canadian Arctic and the North Pacific further increase . Over the US and over central and southern Europe the frequencies strongly decrease (with the exception of the Iberian Peninsula), while they increase over northern Europe and particularly strongly south of Iceland. In~~ in the Northern Hemisphere further increase in the storm tracks (notably south of Iceland) and remain high at polar latitudes. The high frequencies in the storm track regions agree particularly well with the enhanced frequencies of cyclonic RWB there in JJA (**?**). Further, as the North Atlantic and the North Pacific jet streams shift poleward and split-jet conditions over Europe and the US disappear, PV cutoff frequencies in these regions strongly decrease compared to MAM. Instead, over the subtropical North Pacific and the subtropical North Atlantic large northeastward sloping bands of high frequencies appear~~, similar~~. Similarly to their southern hemispheric counterparts in DJF, they are located equatorward of the jet stream in regions with frequent anticyclonic Rossby wave breaking (**?**). The Southern Hemisphere is ~~now~~ dominated by a zonal band between about 30°N and 60°N with local maxima over southern Australia and New Zealand, the central South Pacific, southern South America, and South Africa. These maxima coincide relatively well with maxima of ancyclonic Rossby wave breaking (**?**).

Frequencies in SON (Fig. **??**d) are similar to MAM. Increasing frequencies compared to JJA are discernible over the US, and central and southern Europe, as split-jet conditions start to re-establish. The maxima over the Arctic, in the North Pacific and the two bands in the subtropical North Pacific and North Atlantic are still visible but frequencies substantially decrease compared to JJA. In the Southern Hemisphere, the circumpolar band shifts poleward and becomes more ~~symmetric~~ uniform again and the tilted bands over the South Pacific and South Atlantic start to reappear.

~~To better understand these frequency patterns~~As a first step towards understanding the life cycles of PV cutoffs, it is insightful to look at the ~~patterns~~ geographical locations of genesis and lysis~~frequencies~~. Note again that lysis can be due to reabsorption or diabatic decay. Figures **??** and **??** show seasonal maps of the number of genesis and lysis events per season that occur within a 500 km distance of each grid point. ~~Genesis frequencies are mostly but not always largest where also~~ In some regions, maxima in genesis frequencies disagree with maxima in PV cutoff frequencies~~are largest, indicating variability in cutoff mobility, size, and lifetime in different regions~~. For example, ~~the high frequency over the Mediterranean in DJF (Fig. ??a) does not seem to be linked exclusively to frequent genesis over the Mediterranean~~ while genesis maxima also coincide with cutoff frequency maxima over California and the Mediterranean, genesis is particularly frequent in the eastern part of the storm tracks (Fig. ??a) but ~~also frequent movement of PV cutoffs forming over central and northern Europe into the Mediterranean, where lysis is very frequent~~ PV cutoff frequencies are larger in the western parts (Fig. ~~??~~??a). In the Southern Hemisphere in DJF the well-known (see ~~section~~ Sect. ??) genesis maxima close to the west coast of South America and west of South Africa are visible (Fig. ??a). ~~The lysis maxima in these regions are shifted eastward over land suggesting effects of orography, land-atmosphere interaction, and continental convection on PV cutoff lysis. Generally, it seems that in summer lysis is enhanced over land (~~As PV cutoff frequencies, PV cutoff genesis frequencies can largely be understood as the result of the climatological large-scale flow conditions and corresponding positions of the jet streams in the respective seasons (cf. Fig. ?? and associated discussions). For example, the genesis maxima in the storm tracks are located within or downstream of maxima of cyclonic RWB (??) further indicating that PV cutoffs in the storm tracks are mainly a consequence of cyclonic RWB. For PV cutoff lysis frequencies, additional aspects seem to be important. For example, some lysis maxima occur over land related to orography [e.g.~~in~~ , in DJF and SON over South America and South Africa (Fig. ??a,d), in JJA over the ~~Iberian Peninsula and the~~ Rocky Mountains/Pacific Coast Ranges ~~in~~ and over the Iberian Peninsula (Fig. ??c), and in JJA and SON over Greece, Turkey, and the Balkans (Fig. ??c~~), whereas in winter lysis maxima often~~ ,d)], whereas others occur over sea surfaces, in particular where enhanced sea surface temperatures are expected ~~(~~[e.g.~~in the Mediterranean~~ , in all seasons over the Mediterranean, in JJA over the Caribbean, and in regions of all western boundary currents~~, especially~~ ; e.g., in DJF over the western North Atlantic and ~~east of Australlia; see Fig. ??a,c).~~ in JJA east of Australia]. A further conspicious lysis maximum is discernible over the central US / the southern Rocky Mountains in all seasons~~except JJA. This also indicates effects of orography but may also~~ , which could be related to orography and/or the supply of moist and warm air ~~form~~ from the Gulf of Mexico. These patterns suggest an important role of diabatic effects on PV cutoff lysis, e.g., due to friction and orography, land/sea surface-atmosphere interactions, and convection. However, lysis frequencies are also high in regions where diabatic effects are not expected to be particularly strong, e.g., in the Southern Ocean around Antarctica in all seasons or over Russia and Alaska in DJF.

~~A further interesting aspect is revealed when comparing the lifetime and distance between genesis and lysis in the two hemispheres.Table ?? shows that in both hemispheres, more than 50% of all PV cutoff tracks persist for less than three days and 12-18% for seven days or longer, with a tendency of southern hemispheric PV cutoffsto last shorter. However, comparing the distances between~~ A range of previous studies has addressed climatological frequencies of PV cutoffs. In the following, we relate our results to these studies and summarize the main new insight gained from the results presented here. Many of the presented frequency, genesis and lysis ~~(Table ??) shows that PV cutoffs tend to travel further in~~ maxima of PV cutoffs are consistent with previous climatological studies. In the Southern Hemisphere~~than in the Northern Hemisphere: 62% travel more than 3000~~, most maxima agree well with the results of ?, ?, and ?. In the Northern Hemisphere, they compare favorably with

? mainly in subtropical latitudes, with, e.g., **?** in higher latitudes, and with **?** in most regions if COLs at both 500 ~~km and only 9% less than 1000~~hPa and 200 ~~km in the Southern Hemisphere, versus 48% and 15% in the Northern Hemisphere, respectively. This might be~~ hPa are considered. However, in this study all of them are identified based on a consistent methodology and independent of the selection of a vertical level. This has also implicatons for the seasonality of PV cutoffs. Several previous studies found a clear seasonal cycle with about four times more COLs forming in summer than in winter in both hemispheres but also that seasonality depends strongly on the considered pressure level (**???**). The seasonal cycle in this study is much weaker, in agreement with the findings of **?**, if they took into account all isentropic levels from 305-370 K. Hence, its seems that the strong seasonal cycle found in previous studies is mainly related to the ~~presence of a strong circumpolar jet stream that allows rapid advection of PV cutoffs once they have formed.~~

4 ~~The nature of PV cutoff life cycles~~

~~The tracking procedure introduced in Sect. **??** allows for a comprehensive analysis~~ seasonal cycle of the vertical (pressure or isentropic) level on which PV cutoffs / COLs occur [for illustration of this aspect, see **?**, their Fig. 8b].

Further, some of the identified maxima have not or only little been described in the literature before. In particular, the circumpolar band around Antarctica and the far equatorward reaching band in the South Pacific in DJF have not been documented as regions of COL occurrence yet. The circumpolar band around Antarctica and its seasonal change in symmetry agrees very well with the climatology of upper tropospheric storm track features discussed in **?**. The maximum east of Brazil was mentioned only by **?** and **?**.

Finally, our global analysis reveals also general global patterns of PV cutoff ~~life cycles. In this section, subsets of PV cutoff tracks are investigated, selected according to their genesis region. In DJFand JJA, six genesis regions are selected each such that a broad spectrum of regions is covered (see blue boxes in Fig. **??**a, c, for more details see Table S1 in the supplementary material). In the following, various aspects of the~~ occurrence and its relation to other elements of the atmospheric circulation. PV cutoffs in summer occur frequently in the subtropics mostly in east- and poleward tilted bands reaching latitudes around 20° over the Pacific and Atlantic equatorward of the jet stream, and another one at higher latitudes, in particular in the storm track regions poleward of the jet stream. In winter, PV cutoffs occur either poleward of the jet stream or, particularly frequently, in regions with split-jet conditions between the polar and subtropical jet streams. A comparison to the climatology of jet streams (**?**) further supports these relationships between jet streams and PV cutoffs. It shows that high PV cutoff frequencies often occur slightly poleward of jet frequency maxima (western North Atlantic, Japan, around Antarctica in DJF), poleward of the subtropical jet maxima and equatorward of the polar jet maxima (Mediterranean and central Europe in DJF, Australia in JJA), or in regions where strong jet streams are absent, in particular over the subtropical ocean basins in summer. This link to jet streams will be used for a classification of PV cutoffs in Sect. **??**. Further, some PV cutoff frequency maxima are in striking agreement with high cyclone frequencies. For example, the frequency maxima over the Canadian Arctic and south of Iceland in JJA agree particularly well with the surface cyclone maxima found by **?**. Frequency maxima over the southern Indian Ocean close to Antarctica in DJF also correspond well with surface cyclone maxima identified by **?**. Together with the discussed agreement with frequencies of cyclonic RWB, this suggests that, in particular regions, PV cutoff life cycles are strongly linked to the baroclinic life cycles of ~~PV cutoffs with genesis in these twelve regionsare investigated. We start with a discussion of the synoptic configurations~~ extratropical cyclones. This aspect will be further investigated in Sect. **??** for cutoff categories and in Sect. **??** for selected geographical regions.

3.1 Quantification of diabatic decay and reabsorption

In the following, we address an aspect of PV cutoff ~~genesis. Subsequently, PV cutoff tracks and~~ life cycles that, so far, has not been investigated climatologically: Do they disappear on an isentrope due to diabatic decay or reabsorption to the stratospheric reservoir? According to **?** and based on "synoptic experience", diabatic decay is the dominant scenario. Here, we provide the first quantitative answer to this long-standing question in dynamical meteorology. This quantification will be useful to better understand global climatological patterns of PV cutoff lysis, the modification of PV cutoffs by diabatic processes, as well as their vertical evolution~~and lifetimes are discussed. The vertical evolution is then linked to the occurrence of diabatic decay and reabsorption~~.

Whenever a PV cutoff disappears on an isentropic surface, we quantify what fraction of the PV cutoff experiences diabatic decay (i.e., undergoes STT) and what fraction is reabsorbed by the stratospheric reservoir (see Sect. **??** and Fig. **??**e,f). The diabatic decay fraction of a single cutoff can vary between 0% (pure reabsorption) and 100% (complete diabatic decay). Intermediate values indicate simultaneous partial reabsorption and partial decay. Note that this analysis identifies events on isentropic surfaces, which means that, even if a 2D PV cutoff disappears, the 3D PV cutoff may still persist afterwards. Therefore, reabsorption and decay can, in principle, occur during the entire PV cutoff life cycle. Here, we first investigate the overall statistics of decay and reabsorption and then provide a global overview of the geographical distribution of these two possible scenarios.

Figure **??**a shows the decay and reabsorption statistics for five different categories of the decay fraction for all 2D PV cutoffs identified globally. It shows that almost pure reabsorption (decay fraction $< 25\%$) is equally frequent as complete diabatic decay (decay fraction $= 100\%$), while intermediate scenarios are relatively rare. Considering all events with a decay fraction of $<50\%$ as reabsorption and all other events as diabatic decay shows that reabsorption accounts for almost half (47%) of the disappearances of 2D PV cutoffs. During lysis of 3D PV cutoffs, reabsorption is with a share of 54% even a little more frequent than diabatic decay. This result disagrees with the expectation by **?** that diabatic decay dominates. Figure **??**b,c provides the following explanation for this result: Reabsorption predominantely occurs for large PV cutoffs with comparatively high PV values. For an individual 3D PV cutoff this is usually the case on higher isentropic levels, where it is closer to the stratospheric reservoir. Hence, at higher levels, chances are high that the PV cutoff is reabsorbed by the stratospheric reservoir. It may also occur that the reabsorption is transient, ~~and the evolution of stratosphere-troposphere exchange along the life cycles. To put these aspects into the context of the climatological analysis presented in Sect. ??, their geographical distribution is also discussed.As a first step towards understanding surface impacts of PV cutoffs, the last part of this section investigates the link to surface cyclones, in particular focusing on the chronology of the life cycles of PV cutoffs and surface cyclones.~~

3.2 ~~Synoptic configuration of PV cutoff genesis~~

~~It is well known that the genesis of PV cutoffs is often the result of anticyclonic RWB (e. g. , ??), which occurs on the anticyclonic shear side, i. e., equatorward, of the jet stream and is characterized by an equatorward extending and backward tilted PV streamer (?) that then breaks up into one or more PV cutoffs (?). However, already ? pointed out that also cyclonic RWB may result in cutoff formation. Cyclonic RWB is known to predominantly occur on the cyclonic shear side,~~ i.e., ~~poleward, of the jet stream and is characterized by the cyclonic wrap up of a PV streamer (?) around the surface cyclone,which is positioned poleward of the~~ a PV cutoff is reabsorbed and later again detached from the stratospheric reservoir several times during its life cycle. This behavior has been shown by ? for two case studies over Europe. Complete diabatic decay, on the other hand, occurs typically at lower levels where the PV cutoff is smaller and has lower PV values. We conclude that, on a global average, diabatic decay and reabsorption are equally relevant for the three-dimensional life cycles of PV ~~streamer and classically results in an occluded surface cyclone (??). Given the high genesis frequencies in the storm track regions~~ cutoffs.
The geographical distributions of reabsorption and diabatic decay events of 2D PV cutoffs are visualized in Fig. **??**. The maps show the seasonal mean frequency of reabsorption (Fig. **??**a,c) and decay (Fig. **??**b,d) occurrence within a 500 km distance of a particular grid point in DJF and JJA. The geographical patterns of both categories resemble the PV cutoff frequencies presented in Fig. **??**, revealing that they can both occur during all phases of the life cycle. However, frequencies are particularly high where also lysis frequencies are high (Fig. ~~??),PV cutoffs there are expected to form due to cyclonic RWB. To check whether the genesis of PV cutoffs in the selected regions follows these archetypes, Fig. ?? shows composites of 250 hPa geopotential height anomalies and wind speed, mean sea level pressure, and frequencies of surface cyclones and PV streamers for all genesis events in the six PV cutoff genesis regions selected in DJF. In all regions, geopotential height anomalies show a wave-like pattern with a negative anomaly within and a positive anomaly upstream and~~**??**a,c). Lysis maxima at higher latitudes are preferentially near reabsorption maxima, and at lower latitudes near decay maxima. During DJF, in particular the lysis maxima over the central/~~or poleward of the region of PV cutoff genesis. Also, all regions show high frequencies of stratospheric PV streamers (yellow contours)in the vicinity of the~~ southern US, the US east coast, the Mediterranean, southern South America, South Africa, and southeast of Australia are dominated by diabatic decay and the ones over Alaska, Russia, and the southern Ocean around Antarctica by reabsorption. In JJA, diabatic decay dominates lysis maxima over the western US, the Mediterranean, the Caribbean, South Africa and south of Australia. Reabsorption more strongly contributes to lysis maxima over the northern North Pacific, the Hudson Bay, south of Iceland, and again the southern Ocean around Antarctica. Hence, even if they are roughly equal on a global average, the frequencies of diabatic decay and reabsorption strongly depend on the region.

3.2 Climatological characteristics of PV cutoffs with different positions relative to the jet streams

The discussion of climatological frequencies in Sect. **??** suggested a strong relationship between PV cutoff occurrence and the position of jet streams. Additionally, Sect. **??** showed that a central characteristic of PV cutoff life cycles, the frequencies of decay and reabsorption, has a remarkable regional variability. In this section, we investigate characteristics of the life cycles of PV cutoffs, which differ in terms of their position relative to the jet streams. This not only provides insight into fundamental properties of PV cutoff life cycles, but also serves to explain parts of their regional variability. To this aim, PV cutoffs are classified into three types: Type I forms equatorward of the jet stream, Type II between the polar and the subtropical jet streams, and Type III poleward of the jet stream (for details see Sect. ??). This classification of PV cutoffs according to the jet-relative position follows early studies by ? and ?. According to the considerations in Sect. ?? and the fundamental understanding of RWB and baroclinic life cycles (e.g., ??) the jet-relative position is expected to be strongly linked to the type of wave breaking resulting in PV cutoff formation. ~~This illustrates again the three-dimensional aspect of PV cutoff formation: A PV cutoff initially forms on lower isentropic levels while there is still a PV streamer on higher isentropic levels that may break up at later times. Beside these consistencies, there are substantial regional differences. PV cutoffs with genesis over the eastern South Pacific and South Africa show clear signatures of anticyclonic wave breaking with PV cutoff genesis on the anticyclonic shear side~~ Therefore, the classification used here is also related to the one proposed by ?, which was based on the shape of the breaking upper-level wave. Please note that the supplementary material S3 (Figs. S2-S4) illustrates example cases for each of the three types.

The climatological frequencies of the three types reveal that each occurs in preferred regions with different seasonal cycles (see supplementary material S1, Fig. S1). The summer maximum in the subtropical ocean basins is dominated by Type I cutoffs. In the other seasons, in particular winter and spring, this cutoff type is infrequent. On the contrary, Type II occurs most frequently in winter in mid-latitudes between about 30-50° latitude and particularly frequently in regions with split-jet conditions (e.g., the Mediterranean, California, Australia, New Zealand). Type II hardly occurs in summer and has moderate frequencies in the autumn and spring. Finally, Type III occurs at higher latitudes and in the storm track regions all year around.

The regional differences in their occurrence already suggest that the meteorological environment may strongly vary between the three types. In the following, synoptic composites at the time of PV cutoff genesis are presented for each of the three types. The composites contain all PV cutoffs of the respective type in the dataset, i.e., cutoffs in all seasons and both hemispheres (fields from the Southern Hemisphere are flipped in the meridional direction). The environment of Type I is characterized by a strongly anticyclonic tilt of the potential temperature field at the dynamical tropopause, which is a clear sign of anticyclonic Rossby wave breaking (Fig. ??a). The wave breaking occurs in a region with anticyclonic wind shear equatorward of the jet stream~~and at the eastern flank of asubtropical~~ , as indicated by the composite zonal wind (Fig. ??a). Type I PV cutoffs form over a surface anticyclone and ~~downstream and equatorward of a surface cyclone in the storm track region~~ result in only weak surface precipitation (Fig. ??d~~,e). In the western Mediterranean, PV cutoff genesis occurs on the anticyclonic shear side of the polar jet over the North Atlantic and on the cyclonic shear side of the subtropical jet over northern Africa~~). Type II PV cutoffs are also the result of anticyclonic RWB equatorward of the jet stream, albeit with a weaker anticyclonic tilt (Fig. ??b). Consistently and in contrast to Type I, the wind speed increases also equatorward of the PV cutoff, resulting in a cyclonic barotropic shear and counteracting the anticyclonic tilting of the PV streamer. Such a situation can result in a cyclonic break-up of the tip of the PV streamer (as for the case shown in the supplementary material Fig. S3), featuring a mixture between anticyclonic and cyclonic RWB (?). Type II has the highest precipitation rates among the three types (Fig. ??e). Precipitation is highest east of the cutoff centre, where the sea level pressure field shows signatures of a developing surface cyclone. Finally, Type III cutoffs form from an upper-level wave with no or a slight cyclonic tilt poleward of the jet stream (Fig. ??c). ~~The tilt of the region with~~

~~high PV streamer frequencies and enhanced surface cyclone frequencies between Greenland and Iceland are also indicative of anticyclonic RWB over Europe.Together with the enhanced cyclone frequencies in the genesis region this indicates that first, wave breaking occurs anticyclonically but as the equatorward extending PV streamer is influenced by the cyclonic shear of the subtropical jet , it can break cyclonically to form a PV cutoff located~~ They are associated with a pronounced surface cyclone and substantial precipitation (Fig. **??**f, although less than for Type II).

To gain insight into the quantitative link between PV cutoffs and surface cyclones beyond composites, the two weather systems are linked on an event basis. It is well established that upper-level PV anomalies can play an important role for the genesis and intensification of surface cyclones (e.g., **?????**) and thereby strongly affect surface weather. As noted in the introduction, PV cutoffs have been linked to surface cyclones for individual cases or climatologically within certain regions. While most studies focused on surface cyclones and then considered potentially associated upper-level PV anomalies, here, we focus on PV cutoffs and ask how often we find surface cyclones in their proximity (for methodological details see Sect. **??**). Consistent with the composite sea level pressure, the frequency with which a PV cutoff is close to a surface cyclone during its life cycle varies substantially among the three types (see percentages in Fig. **??**d-f). More than half of Type III cutoffs, almost 40% of Type II cutoffs and less than 8% of Type I cutoffs are linked to surface cyclones. It is also interesting to note that even for Type III, a substantial fraction of PV cutoffs is never linked to a surface cyclone.

These results reveal that there are fundamental meteorological differences between the three PV cutoff types, supporting the view point that the formation of PV cutoffs with different jet-relative positions can be understood as a result of the two archetypal baroclinic wave life cycles (LC1 and LC2, **?**). LC2 results in cyclonic RWB and PV cutoffs poleward of the jet stream, often close to the surface cyclone (Type III). LC1 results in anticyclonic RWB and PV cutoffs equatorward of the jet stream in summer (Type I), and between the polar and the subtropical jet streams ~~. A similar but less clear scenario occurs also over California (Fig. **??**a). The synoptic pattern in the~~ in winter (Type II). These PV cutoffs are well separated from the primary surface cyclone (which generally remains confined to the storm track regions~~(western North Atlantic and southern Indian Ocean close to Antarctica)strongly resembles cyclonic wave breaking resulting in a PV cutoff poleward of the jet stream (Fig. **??**b, f). Enhanced cyclone frequencies just below and slightly poleward of the stratospheric PV streamer, on the cyclonic shear side of the jet stream are clear indicators of this~~). However, the formation of Type II cutoffs can be related to secondary cyclogenesis downstream of the primary surface cyclone. From an impact point of view, Type II cutoffs are of particular interest. They are not only associated with the highest precipitation rates and a significant influence on the surface pressure field, but also frequently occur in populated areas.

Next, some basic characteristics of the life cycle of the three PV cutoff types are analyzed and compared. To this aim, empirical distributions of six characteristics are shown for each type in Fig. **??**. For continuous variables we show density distributions and for discrete variables normalized histograms. The lifetime shows a roughly exponential decay after the minimum duration of one day required in this study. The distributions are very similar for the three cutoff types, with a tendency for Type I cutoffs to last shorter than the others (Fig. **??**a). Larger differences appear for the spherical distance between genesis and lysis, which is substantially smaller for Type I cutoffs (Fig. **??**b). ~~These results and interpretations are consistent with the maxima of anticyclonic (cyclonic)wave breaking over the southwestern US and central Europe (the North Atlantic)found by **?**.~~ The mean is slightly above 2000 km, while it is about 50% larger for Types II and III. Consistently, the average propagation speed is also lowest for Type I, followed by Type II and Type III. These differences are of course related to the preferred regional occurrence of the three types. While Type I occurs preferentially in regions with low climatological zonal wind speed, Type III occurs in the storm tracks, where zonal winds are stronger. Type II occurs in regions with moderate zonal wind speed and consequently, its propagation speed is intermediate. These results also show that the picture that PV cutoffs are mainly quasi-stationary systems is misleading. In fact, many PV cutoffs travel several thousand kilometers. This result stands in contrast to studies pointing out the quasi-stationarity of COLs (e.g., **??**) or even assume it to justify assumptions for the tracking procedure (e.g., **?**). The frequent occurrence of PV cutoffs with lifetimes between 1-2 days is in agreement with earlier studies (e.g., **???**), except from **?**, who found average lifetimes of 6-8 days. Differences in mobility and lifetime most likely arise from the different identification and tracking methods.

~~Figure **??** shows similar results for JJA, although with substantially weaker geopotential height anomalies and lower wind speeds in the Northern Hemisphere. PV cutoffs over the central and eastern subtropical North Atlantic form from anticyclonic wave breaking equatorward of the jet stream~~ Two other key characteristics of PV cutoff life cycles are the frequencies of decay and reabsorption. Section **??** already pointed out that substantial regional differences exist. Here, we find that for Type III cutoffs reabsorbtion is more frequent and, consistently, decay less frequent than for the two other types (Fig. ~~**??**b,c)and PV cutoffs in the Hudson Bay show signatures of cyclonic wave breaking~~ **??**d,e). More than 80% of all Type III PV cutoffs experience at least one reabsorption event, but only slightly less than 60% experience a decay event. For Type I, these numbers are 65% for reabsorption and 80% for decay. Also here, Type II has intermediate values. A reason for these differences could be that Type I and Type II cutoffs are generally further away from the stratospheric reservoir, rendering reabsorption less probable.

Finally, the mean isentropic level of the PV cutoff during its life cycle is considered (Fig. ~~**??**a). Over Australia and the Baltic Sea, the synoptic patterns are similar to the one in the Mediterranean, with first anticyclonic, and subsequent cyclonic wave breaking (Fig.**??**d, f) . However, the combined scenario over Australia, in contrast to the Mediterranean, does not show many surface cyclones in the genesis area. Over the Sea of Okhotsk the scenario is less clear (Fig. **??**e).~~ **??**f). Consistent with earlier studies and the composite analyses (Fig. **??**a-c), the differences between the three types are substantial. Type I occurs mainly above 325 K, Type II between 300 K and 320 K, and Type III between 290 K and 305 K. In addition, the distribution is narrower for Type III compared to the other two types. These results further demonstrate the importance of considering a large range of isentropic levels to capture all PV cutoffs in different regions and seasons.

4 PV cutoff life cycles in selected genesis regions

In the first part of this article, global patterns and characteristics of PV cutoff life cycles were discussed and it was shown that the position relative to the jet streams helps to explain some of the large variability of PV cutoff life cycles. Previous case studies (e.g., **?????**) suggested that the life cycles of PV cutoffs including their surface impacts can also be strongly modified by characteristics of a specific geographical region (e.g., orography, moisture availability, and sea surface temperatures). In addition, there is a particular interest in the scientific community to study PV cutoffs and their impacts in specific geographical regions systematically, for example in Europe and the Mediterranean (e.g., ?), North America (e.g., ?), East Asia (e.g., ?), South America (e.g., ?), South Africa (e.g., ?), and Australia (e.g., ?). Therefore, in this section, subsets of PV cutoff tracks are investigated, selected according to their genesis within clearly defined geographical regions. This approach is complementary to the separation of PV cutoffs according to their jet-relative position. We demonstrate here that the global climatology is useful to perform regional analyses of PV cutoffs based on a consistent methodology, allowing for a better quantitative comparison of PV cutoff life cycles across geographical regions than it was previously possible.

~~It has to be kept in mind that behind the composite structures there can be a high variability in the wave breaking between individual cases. In particular,~~ In DJF and JJA, six genesis regions are selected subjectively, also considering regions that were previously discussed in the literature (see black boxes in Fig. **??**a,c; for more details see Table S1 in the supplementary material). This selection does by no means include all interesting regions (it contains roughly 6% of cutoff tracks in the ~~PV streamer may not be tilted but rather meridionally aligned, or that a PV streamer is not present at all, as it seems to occur for many cases over the Hudson Bay. Nevertheless, the results~~ dataset) and we encourage the community to use our dataset for further analyses. In the following, various aspects of the life cycles of PV cutoffs with genesis in these twelve regions are investigated. We start with a discussion of PV cutoff tracks and then discuss their vertical evolution and lifetimes. The vertical evolution is then linked to the occurrence of diabatic decay and reabsorption along the life cycles. Finally, the last part of this section ~~provide clear evidence for distinct wave breaking scenarios leading to PV cutoffs in different regions.~~ investigates the link to surface cyclones, in particular focusing on the chronology of the life cycles of PV cutoffs and surface cyclones.

4.1 PV cutoff tracks

~~Next~~First, an overview of the tracks is ~~given~~ presented for all selected genesis regions. Figure **??** shows the tracks and lysis points for the six regions selected in DJF. ~~For~~ In all regions, PV cutoffs tend to travel eastward. Most PV cutoffs forming over California move across the Rocky Mountains, where some tracks already end (Fig. **??**a), consistent with the lysis maximum there in Fig. **??**a. However, many continue to move northeastward over the southern and eastern US, and some even travel far into the North Atlantic. PV cutoffs forming over the ~~western North Atlantic mostly remain over the North Atlantic, some travel into the Arctic Ocean, and a few over Europe and into the Mediterranean~~ Nordic Seas often remain in this area or move towards Northern Europe, but some even propagate into the Mediterranean, towards the North Pole, or across Russia (Fig. **??**b). PV cutoffs with genesis over the western Mediterranean first travel southeastward across the Mediterranean and then tend to move on a more eastward or northeastward path over eastern Europe and the Middle East, where many tracks end (Fig. **??**c). ~~Very few end their life cycle in the genesis box.~~ The tracks with genesis over the eastern South Pacific and over South Africa are strikingly similar (Fig. **??**d,e): they lead southeastward across the southern tips of South America ~~(South Africa)~~ and South Africa, where many tracks end over land~~and some reach~~ , and some cutoffs travel further into the South Atlantic ~~(South Pacific). PV cutoffs~~ and the South Pacific, respectively. However, PV cutoffs over South Africa travel on average about 400 km farther. PV cutoffs forming close to Antarctica travel ~~far~~ relatively zonally eastward and a few almost fully around Antarctica (Fig. **??**f). In each of the regions one particular PV cutoff type dominates but to differing extents. For example, over the Nordic Seas and the Antarctic Ocean, Type III is most frequent. However, while it strongly dominates over the Antarctic Ocean (almost 90% of the cases), Type II is also frequent over the Nordic Seas (only 70% of Type III). The average spherical distance between genesis and lysis ranges between 1860 and 2353 km and is therefore well within the interquartile range of all types shown in Fig. **??**b.

In JJA (Fig. **??**), PV cutoffs also ~~mostly travel eastward~~ travel eastward on average in all selected regions except the ones forming over the central subtropical North Atlantic (Fig. **??**~~b~~a). There, they tend to move along a northeastward tilted band in either direction or remain stationary (many end their life cycle in the genesis box). ~~Together with PV cutoffs forming over the eastern subtropical North Atlantic (Fig. **??**c), they contribute to the lysis maximum over the Iberian Peninsula (Fig. **??**c). PV cutoffs with genesis over the Hudson Bay (Fig. **??**a) and the Sea of Okhotsk~~ In all regions except Australia, most PV cutoffs do not travel very far and most of them end their life cycles within or slightly outside of the genesis box (Fig. **??**~~e), i. e. at the beginning of the North Atlantic and North Pacific storm tracks, move eastward and contribute to the high lysis frequencies in the centre and at the end of the storm tracks (see Fig. **??**c). PV cutoffs forming over the Baltic Sea are relatively stationary and mostly end their life cycle in northeastern Europe or western Russia (Fig. **??**d). Finally~~a-e). The average travel distance of cutoffs from the northern hemispheric genesis regions ranges from 1277 to 1557 km, which is near the lower quartiles of the distributions of all cutoffs of the three types (Fig. **??**b). This is consistent with the generally lower zonal wind speed in Northern Hemisphere summer compared to the other seasons. On the contrary, cutoffs with genesis ~~over~~ southwest of Australia are very mobile with many of them moving out of the genesis box across southeastern Australia and some far into the South Pacific or the Antarctic Ocean (Fig. **??**f).

4.2 Vertical evolution and half lifes

Further differences and similarities of the life cycles of PV cutoffs forming in the selected regions ~~become apparent when looking at~~ appear in composites of their vertical evolution. Figure **??** shows, for each of the six genesis regions selected in DJF, the frequency of PV cutoffs on all considered isentropic levels during their life cycle. First, it becomes obvious that the isentrope with the highest frequency and the vertical range of isentropes with PV cutoffs vary substantially between regions. For example, PV cutoffs over California can be found at levels from 290 K up to ~~345~~340 K (Fig. **??**a), whereas over the Mediterranean they are restricted to levels below 330 K (Fig. **??**c), even if the level with the highest frequency is similar (~~310-315~~around 310 K in both regions). ~~Also~~ PV cutoffs close to Antarctica occur preferably between 295-315 K (Fig. **??**f), whereas PV cutoffs forming over the eastern South Pacific and South Africa occur from ~~310~~305 K up to ~~350~~345 K (Figs. **??**d,e). ~~Figure **??** also shows that the frequencies are highest about one day after genesis and for some regions the frequency maximum rises to higher levels during the days after genesis (~~This of course reflects to some extent the differences between the cutoff types (Fig. **??**f). But the differences between regions where the same cutoff type dominates (e.g.~~California, western North Atlantic, the Mediterranean~~, ~~see~~ Calfornia and Mediterranean) show that specific regional aspects are important, too.

In all regions, frequencies are highest about one day after genesis (Fig. **??**~~a-e~~). A main reason for ~~these two properties~~ this is that PV cutoffs form on a lower isentropic level first and as the break-up of the PV streamer continues, additional vertical levels become part of the PV cutoff until it reaches its full vertical extent. Interestingly, the timescale of roughly one day until reaching the maximum ~~frequency~~ extent is consistent across all regions, indicating that it can serve as ~~a global~~ an estimate of the average time required for the complete break-up of a PV streamer into PV cutoffs. In addition, for PV cutoffs over the eastern South Pacific and South Africa, the frequencies increase also below the level of maximum frequency during the first day. The only explanation for such an evolution is that these PV cutoffs grow downward, indicative of troposphere-to-stratosphere transport. On the contrary, for PV cutoffs over the Mediterranean the frequencies below the level of maximum frequency decrease rapidly, indicating diabatic decay and stratosphere-to-troposphere transport. For Antarctica, there is not much vertical displacement during the first two days, indicative of a rather adiabatic evolution.

After one day, the cutoff frequency gradually decreases in all regions and the number of active cutoff tracks follows relatively closely an exponential decay. This ~~indicates~~ shows that the probability of a PV cutoff track to end is relatively constant, i.e.~~the "death"~~, the lysis of PV cutoffs can be regarded as an exponential decay process. We use an exponential curve fitted to the number of active tracks after genesis to estimate the half life $\tau_{1/2}$ of the PV cutoffs once they have overcome the 24 h minimum duration required in this study. This value ~~ranges between 38~~is surprsisingly similar across regions and ranges from 25 h (South Africa) ~~and 64~~to 31 h (Mediterranean). Hence, the median lifetime is between ~~52 and 88~~49 and 55 h and the expected (i.e., mean) lifetime $\overline{T}$ [computed as ~~$\overline{T} = 24h + \tau_{1/2} \cdot \ln(2)^{-1}$~~$\overline{T} = 24\,\mathrm{h} + \tau_{1/2} \cdot \ln(2)^{-1}$] between ~~79 and 116~~60 and 69 h. ~~This reveals that the lifetime of PV cutoffs is highly variable between regions .~~Hence, across the regions considered, the lifetimes do not vary strongly and expected lifetimes are close to the mean lifetimes of the three cutoff types (Fig. **??**a).

A similar picture appears for JJA (Fig. **??**), where maximum frequencies are also found roughly one day after genesis in all regions~~and they decay~~, decaying approximately exponentially afterwards. ~~Interestingly, the isentrope of maximum frequency gradually decreases during the life cycle of the~~ Downward growth is also apparent for PV cutoffs over the central and eastern subtropical North Atlantic (Fig. **??**a,b), ~~indicating a downward growth,~~ while over Australia ~~it rises rapidly by more than 5 K within the first two days~~ PV cutoffs rapidly disappear at lower levels (Fig. **??**f)~~, indicating rapid decay at lower levels. Striking is also~~. A further interesting aspect is the gradual lowering of the isentropic level with the maximum frequency along the transect of genesis regions from the central to the eastern subtropical North Atlantic and to the Mediterranean (Fig. **??**a-c), consistent with an increase in latitude. Particularly noteworthy is the very large half life (~~114~~70 h, ~~$\overline{T} = 188$~~$\overline{T} = 125$ h) of ~~the~~ PV cutoffs forming over the central subtropical North Atlantic~~(Fig. ??b)~~, which is more than two times longer than ~~for the neighboring region over the eastern subtropical North Atlantic (Fig. ??~~in all other regions. On the contrary, PV cutoffs over the Mediterranean have a substantially shorter half life (22 h, $\overline{T} = 52$ h) than in all other regions, in particular also than PV cutoffs in the same region in DJF (Fig. **??**c). PV cutoffs forming over the ~~Sea of Okhotsk and the Hudson Bay are also relatively long lived with half lifes of 90 h and 69 h, respectively (Fig. ??a,e), while the ones over the Baltic Sea and Australia haveshorter half lifes of 58 h and 51 h~~Hudson Bay and the Baltic Sea have, similarly to PV cutoffs near Antarctica in DJF, not much vertical displacement.

4.3 Diabatic decay and reabsorption

The climatological vertical evolution of the 3D PV cutoffs discussed in the previous section is determined by the appearance and disappearance of 2D PV cutoffs on isentropic levels. A PV cutoff appears on an isentropic level either during the break-up process or as it grows downward, involving TST. While these processes are not directly quantified in this study, the processes leading to disappearance, i.e., diabatic decay and reabsorption, are. ~~Whenever a PV cutoff disappears on an isentropic surface, it is quantified what fraction of the PV cutoff experiences diabatic decay (i.e. undergoes STT) and what fraction is reabsorbed by the stratospheric reservoir (see section?? and Fig. ??e, f). The diabatic decay fraction can vary between 0% (pure reabsorption) and 100% (complete diabatic decay). Intermediate values indicate simultaneous partial reabsorption and partial decay. Note that this analysis identifies events on isentropic surfaces, which means that, even if a 2D PV cutoff disappears, the 3D PV cutoff may still persist afterwards. Therefore, reabsorption and decay do not necessarily occur only during PV cutoff lysis. Here, we first investigate the global statistics of~~ In this section, the frequencies of diabatic decay and reabsorption ~~, then use the quantification to provide further insight into the vertical characteristics of the climatological life cycles , and finally provide a global overview of the geographical distribution of these two possible scenarios.Figure ??a shows the decay and reabsorption statistics for five different categories of the decay fraction for all 2D PV cutoffs identified globally. It shows that almost pure reabsorption (decay fraction $< 25\%$) is equally frequent as complete diabatic decay (decay fraction $= 100\%$), while intermediate scenarios are relatively rare. When considering all events~~ are discussed for the life cycles of PV cutoffs in the selected genesis regions. As in Sect. ??, all disappearance events of 2D PV cutoffs with a decay fraction less than 50% are considered as reabsorption and all other events as diabatic decay~~, reabsorbtion accounts for almost half (47%) of the disappearances of 2D PV cutoffs. During lysis of 3D PV cutoffs, reabsorption is with~~ .

First, we discuss the overall frequencies with which a PV cutoff in a certain genesis region in DJF experiences at least one reabsorption event (f_r, see Fig. ??) or at least one decay event during their life cycle (f_d). They vary substantially between roughly 50% and well above 80% across regions. Consistent with Fig. ??d,e, cutoffs in regions where Type III dominates (Nordic Seas, Antarctica) have the highest reabsorption frequencies and the lowest decay frequencies and vice versa for regions where Type I dominates (eastern South Pacific, South Africa). In regions with mostly Type II cutoffs (California, Mediterranean), both scenarios occur roughly equally frequently. It is also noteworthy that the frequency with which a ~~share of 54% even a little more frequent than diabatic decay. This result disagrees with the expectation by ? that diabatic decay dominates. Figure ??b,c provides the following explanation for this result: Reabsorption predominantely occurs for large PV cutoffs with comparatively high PV values. For an individual 3D PV cutoff this is usually the case on higher isentropic levels,where it is closer to the stratospheric reservoir. Hence, at higher levels, chances are high that the PV cutoff is reabsorbed by the stratospheric reservoir. It may also occur that the reabsorption is transient, i.e. a~~ PV cutoff ~~is reabsorbed and later again detached from the stratospheric reservoir several times during its life cycle . This behavior has been shown by ? for two case studies over Europe. Complete diabatic decay, on the other hand, occurs typically at lower levels where the PV cutoff is smaller and has lower PV values.~~ experiences at least one decay event during the life cycle is 20 percent points larger over the Nordic Seas than close to Antarctica, even if Type III dominates in both regions. This shows clearly that regional aspects are also relevant.

~~This aspect is now discussed further for the selected genesis regions. Again, all disappearance events of 2D PV cutoffs with a decay fraction less than 50% are considered as reabsorption and all other events as diabatic decay.The vertical distribution~~ These overall frequencies are complemented by the vertical distributions and temporal evolution of reabsorption and diabatic decay ~~events for the genesis regions in DJF is shown in~~ frequencies (Fig. **??**~~. Indeed, in all regionsthe diabatic decay maxima~~). In all regions, diabatic decay tends to occur at lower levels than ~~the reabsorptionmaxima. Hence, the reduction~~ reabsorption. In fact, diabatic decay is mainly responsible for the decrease of PV cutoff frequencies ~~with lifetime (see~~ (as shown in Fig. **??** ~~) is, at lower levels, mainly due to diabatic decay, and at higher levels due to reabsorption. Beside these common aspects, the temporal evolution and relative frequencies of diabatic decay andreabsorption substantially differ between regions. For example, over California, the Mediterranean and the western North Atlantic (Fig. ??a,b,c), PV cutoffs experience frequently diabatic decay already immediately after genesis~~ and black contours in Fig. **??**) below the level of maximum frequency, reabsorption rather leads to the reduction in frequencies above and, ~~while~~ hence, the combination of the two determines the climatological vertical evolution. Consistent with the exponential decay of the number of PV cutoffs after 1 day, decay and reabsorption frequencies are particularly high between about 1-2 days after genesis in all regions. However, while only a low fraction of PV cutoffs over the eastern South Pacific and South Africa ~~(Fig.??d, e), this is the case only about one day later. PV cutoffs with genesis over Antarctica experience only rarely diabatic decay, which explains the rather adiabatic evolution without vertical displacement of the maximum frequency. Lysis of the 3D PV cutoffoccurs as diabatic decay with a frequency of around 60% for PV cutoffs forming over the eastern South Pacific and South Africa, and a bit less frequently for PV cutoffs with genesis over California (55%) and the Mediterranean (47%; indicated by the numbers on the top right in each panel). For PV cutoffs forming in the storm track regions (western North Atlantic, Antarctica), this value is substantially lower, i.e. a majority of the~~ experiences decay during the first 12 h after genesis, this occurs more frequently for cutoffs in the other regions. This indicates differences in the timing of diabatic activity related to the PV cutoff.

In JJA (Fig. **??**) the values of f_r and f_d also vary across regions. However, here, regions with the highest f_r (well above 80%) are dominated by Type I cutoffs (central and eastern subtropical North Atlantic), which is significantly higher than the climatology of Type I (f_r=66%). PV cutoffs ~~there end their life cycle with reabsorption~~over the Mediterranean , which are also dominated by Type I, have a lower f_r of 60%. Noteworthy is also the significantly lower f_r of PV cutoffs over the Mediterranean in summer than in winter, consistent with the climatological differences between Types I and II.

~~In JJA (Fig. ??) the general pattern with decay~~ The vertical distributions and temporal evolutions of decay and reabsorption frequencies show in JJA a similar general pattern as in DJF with a tendency for decay to occur at lower levels and reabsorption at higher levels~~is similar to DJF.~~ . Both scenarios are particularly frequent betwen 1-2 days lifetime. Reabsorption rarely occurs during the first 12 h while, in some regions, decay is already quite frequent initially. This is likely the case because PV cutoffs are still in the break-up stage. Unexpected are the frequent decay events on 335 K for PV cutoffs over the central subtropical North Atlantic (Fig. **??**~~b~~a), as at the same time the ~~frequencies at these levels increase over time~~cutoff frequency at this level remains fairly constant. This indicates that the many decay events must be ~~overcompensated~~ compensated by the downward extension (i.e.~~many appearances at lower levels~~, many appearances), such that~~on average~~ , on average, these PV cutoffs ~~grow downward. In all other regions, the maxima of diabatic decay (reabsorption) are consistent with a reduction of PV cutoff frequencies at lower (higher) levels. Particularly frequent decay is observed for PV cutoffs over Australia (Fig. ??f). In most regions, diabatic decay is less frequent during lysis than reabsorption, consistent with the global average. The highest ratios of diabatic decay events during lysis (between 40 and 50%) are found for the central and eastern subtropical North Atlantic,~~

~~the Baltic Sea, and Australia. The lowest ratios are found for the Hudson Bay and the Sea of Okhotsk, i.e. in these regions lysis mainly occurs as reabsorption. In fact, in both regions and especially over the Sea of Okhotsk, reabsorption dominates during the whole life cycle.Returning again to all PV cutoffs in DJF and JJA, the geographical distributions of reabsorption and diabatic decay events of 2D PV cutoffs are visualized (Fig. **??**). The maps show the seasonal mean frequency of reabsorption (Fig. **??**a,c) or decay (Fig. **??**b,d) occurrence within a 500~~do not decay on 335 ~~km distance of a particular grid point in DJF and JJA. The geographical patterns of both categories resemble~~ K during several days.

4.4 Link to surface cyclones

Finally, we analyze the link of PV cutoffs to surface cyclones in the different genesis regions. Similarly to Sect. **??** and with the approach described in Sect. **??**, we identify situations where PV cutoffs are located near surface cyclones and ask: How frequently are PV cutoffs linked to a surface cyclone in the different regions? In addition, we analyze how this frequency changes with the lifetime of the PV cutoff~~frequencies presented in Fig. **??**. This reveals that they can both occur during all phases of the life cycle. However, frequencies are particularly high where also lysis frequencies are high (Fig. **??**a, c). Lysis maxima at higher (lower) latitudes are preferentially near reabsorption (decay) maxima, showing that the prevailing lysis mechanism, similar to the genesis mechanism, is dependent on the latitude, i.e.region.During DJF, in particular the lysis maxima over the central/southern US, the US east coast, the Mediterranean, southern South America, South Africa, and south of Australia are dominated by diabatic decay and the ones over Alaska, south of Greenland, northeastern Russia, and the southern Ocean around Antarctica by reabsorption. In JJA, diabatic decay dominates lysis maxima over the western US, the Iberian Peninsula, South Africa and south of Australia. Reabsorption more strongly contributes to lysis maxima over the northern North Pacific, the Hudson Bay, south of Iceland, and again the southern Ocean around Antarctica. Some conspicuous decay and reabsorption maxima occur that cannot directly be related to lysis maxima. They are mainly located in the tilted subtropical bands in summer (consistent with Fig. **??**b). This is likely related to the longevity and quasi-stationarity in combination with the diabatically active lower levels of~~ . Finally, we investigate how PV cutoff life cycles and and cyclone life cycles are temporally linked, e.g., address the questions: Does cyclogenesis occur before or after PV cutoff genesis? If it occurs afterwards, does it occur in the vicinity of the PV cutoff? Answering these questions will not only provide information on how the surface impact of PV ~~cutoffs in this region. These PV cutoffs may experience frequent transient reabsorption events and it may also happen frequently that a PV cutoffdecays and reappears again at a lower isentropic level (i.e transient decay events, see also supplementary material S3, Figure S1).~~

4.5 ~~Stratosphere-troposphere exchange~~

~~Diabatic modification of PV cutoffs (i.e. TST and STT) does not only occur when they appear or disappear on an isentropic surface but potentially during the whole life cycle. In this section, we first investigate how STT and TST mass fluxes evolve during the life cycles of the PV cutoffs in the selected genesis regionsand, second, discuss the geographical distribution of net cross-tropopause mass fluxes. The mass fluxes due to merging and splitting are comparably small and are therefore not considered further. As PV cutoff lifetimes are very variable, a more meaningful comparison of STT and TST of individual~~

~~tracks is achieved by normalizing the tracks between the fix points genesis and lysis (for further details see supplementary material S1). STT and TST along normalized life cycles are shown in Figs. **??** and **??**. For all~~ cutoffs varies across regions, but also on how PV cutoff life cycles are linked to the life cycle of the low-level baroclinic wave signal in the different regions. Figure **??** provides the relevant information for the genesis regions in DJF~~(Fig. **??**), TST is highest during genesis and gradually decreases towards the end of the life cycle . For PV cutoffs with genesis in California and the Mediterranean, STT is generally larger than TST and shows a u-shaped evolution, with high STT values around genesis and lysis (Fig. **??**a,c). This results in particularly large negative net mass fluxes (i.e. the difference between TST and STT) towards the end of the life cycles, indicating that the PV cutoff shrinks due to diabatic processes (subsequently referred to as 'diabatic erosion'). Increasingly large negative net mass fluxes during the life cycle also occur for~~ . The frequencies with which a PV cutoff is linked to a surface cyclone during its life cycle (f_{cy}) varies strongly across regions, mostly consistent with Fig. **??** and the dominant cutoff types in each region. PV cutoffs over the ~~eastern South Pacific and South Africa~~ Nordic Seas and Antarctica (Fig. ~~**??**d,e). There, TST gradually decreases and STT increases (eastern South Pacific) or remains fairly constant (South Africa), rather than showing a u-shaped evolution.As a result, net mass fluxes are small at the beginning of the life cycle.A strikingly different behavior occurs for PV cutoffs in the~~ **??**b,f), i.e., in storm track regions~~(western North Atlantic and Antarctica, Fig. **??**b,f), where both, STT and TST, decrease and net fluxes remain fairly constant during the life cycle, with STT slightly dominating over TST over the western North Atlantic and vice versa over Antarctica. The dominance of TST over STT over Antarctica is striking because it indicates that PV cutoffs there tend to grow rather than decay. The evolutions of STT and TST in good agreement with the numbers of reabsorption and decay events during the normalized life cycle (numbers at the bottom of each panel in Fig. **??**). When STT is much larger than TST, diabatic decay is more frequent than reabsorption, for example towards the end of the life cycle of PV~~ , are linked to surface cyclones in 58% and 68% of the cases, which is even higher than the climatological value for Type III. The lowest frequencies (28-33%), albeit well above the climatological value of Type I, occur for cutoffs over the eastern South Pacific ~~(Fig. **??**d). Vice versa, when TST is larger than STT, reabsorption is more frequent than decay, as for the whole life cycle of~~ and California. PV cutoffs over ~~Antarctica. In all regions, the highest frequencies of both reabsorption and decay occur during the last part of the life cycle, consistent with the geographical agreement of maxima of 2D PV cutoff decay/reabsorption events and lysis maxima of 3D PV cutoffs (Figs. **??**a,c and **??**).In JJA (Fig. **??**), similar STT and TST evolutions can be observed. PV cutoffs with genesis over Australia and the Baltic Sea show a u-shaped STT evolution with STT dominating over TST (Fig. **??**d,f), similar to California and the Mediterranean in DJF. A u-shaped evolution of STT also occurs over the Sea of Okhotsk, but net mass fluxes remain comparably small and in the middle of the life cycle TST even tends to dominate over STT (Fig. **??**e). Net mass fluxes also remain fairly low and STT and TST fairly constant~~ the Mediterranean and South Africa have intermediate frequencies, close to the climatological frequency of Type III. The high frequencies for PV cutoffs ~~forming over the Hudson Bay (Fig. **??**a) . Sea of Okhotsk and Hudson Bay show an evolution most similar to Antarctica and western North Atlantic in in DJF. An interesting evolution occurs for PV cutoffswith genesis in the central and eastern subtropical North Atlantic (Fig. **??**b, c): During the first about three quarters of the life cycle, TST dominates over STT. Afterwards, STT starts to increase and finally becomes larger than TST. This shows that PV cutoffs in these regions first grow diabatically and only late in their life cycle diabatic erosion dominates. Again, reabsorption tends to be more frequent than~~

~~decay for regions where STT is roughly equal or smaller than TST, for example for the Hudson Bay and the Sea of Okhotsk (Fig. **??**a,e). Diabatic decay dominates for regions where STT is larger than TST, for example during the first four fifths of the life cycle for PV cutoffs over Australia (Fig. **??**f). Interestingly, during the last fifth of the life cycle for this region , reabsorption dominates even if STT is much larger than TST. This indicates that , most likely, these PV cutoffs approach the stratospheric reservoir, rendering reabsorption more likely to occur at higher isentropic levels, while they experience substantial STT and diabatic decay at lower levels. The case study in the supplementary material S3 (Figure S2) confirms this behavior.A similar evolution occurs over the Baltic Sea and over the Mediterranean in DJF (Fig. **??**c).~~ over South Africa (46%) are noteworthy as many of them are Type I cutoffs, which, climatologically, are only rarely linked to surface cyclones. The generally higher frequencies compared to what could be expected from the climatological frequencies of the dominant type in each region indicate that in the considered regions cutoffs are particularly relevant for surface cyclones.

~~Considering all PV cutoffs during DJF and JJA, the geographical distribution of average net cross-tropopause mass fluxes (TST minus STT) during the presence of a PV cutoff is visualized for both seasons in Fig. **??**. Distinct regions with enhanced negative cross-tropopause mass fluxes appear. In DJF (Fig. **??**a) these are the western parts of the North Atlantic and the subtropical North Pacific, the lee of the southern Rocky Mountains, the Middle East, southern South America and western South Atlantic~~The frequency of PV cutoffs linked to surface cyclones as a function of lifetime increases over California, the eastern South Pacific, South Africa, and ~~south-western Indian Ocean, and southern Australia and the western South Pacific. In JJA (Fig~~Antarctica during the first couple of days (red curves in Fig. **??**a,d,e,f). ~~**??**b) large negative mass fluxes occur mainly in the vicinity of high orography in the Northern Hemisphere (the northern Rocky Mountains,the Alps,the Caucasus,Central Asia)and around the western and subtropical parts of the ocean basins in the Southern Hemisphere, with particular hot spots over coastal southern Brasil, western Australia, and the subtropical South Pacific. Clear regional patterns also appear for enhanced positive net mass fluxes. They mainly occur over the subtropical ocean basins in the summer season and in polar regions. This striking change of the sign of the average net mass fluxes related to PV cutoffs between regions also agrees well with the life cycle perspective for the selected genesis regions discussed above. There are preferred regions where PV cutoffs are predominantely eroded diabatically and where they remain adiabatic or even grow diabatically. In conclusion, the probability of a PV cutoff to experience diabatic erosion is dependent more on where it is than how old it is. The geographical regions with strongly negative net mass fluxes qualitatively agree well with certain diabatic decay and lysis maxima.~~

4.5 ~~Link to surface cyclones~~

~~In this final results section, a step is made towards understanding the surface impacts of PV cutoffs~~ This shows that PV cutoffs linked to surface cyclones are particularly long lived. Because PV cutoffs that are initially linked to surface cycones are not exceptionally long lived (not shown), an explanation could be that longer lived PV cutoffs result in cyclogenesis later during their life cycle. ~~While it is well known that PV cutoffs can be associated to surface cyclones in some regions, the linkage between PV cutoff life cycles and cyclone life cycles and how it varies between regions has not been investigated systematically. Therefore,the main question addressed in this section is: When during their life cycle are PV cutoffs linked to surface cyclones and how old are these cyclones?~~ This reason could also explain why the frequency of PV cutoffs forming over the Nordic Seas and in particular the Mediterranean initially decreases but shows a secondary peak after 2 and 3 days, respectively (Fig. **??**b,c).

~~An insightful way to address this question is to count~~ This aspect can be partly resolved by counting all PV cutoffs that are at lifetime t_{cutoff} linked to a surface cyclone at lifetime $t_{cyclone}$ and show these ~~counts~~ frequencies in a t_{cutoff} vs. $t_{cyclone}$ diagram ~~. A link is identified where the centre of a surface cyclone is within a distance of 600 km around the PV cutoff centre. Note that both, PV cutoffs and surface cyclones, are required to have a minimum lifetime of one day in this study. Figure **??**shows such a diagram for the genesis regions in DJF~~(shading in Fig. **??**). For example, the ~~green/blue boxes~~ yellow and black colors in the leftmost column in Fig. **??**~~b~~ f show that, at their genesis, ~~PV cutoffs over the western North Atlantic are preferentially~~ about 20% of the PV cutoffs close to Antarctica are linked to surface cyclones that are ~~about 1-3~~ between 1-2 days old. The diagonal displacement of these ~~green/blue boxes~~ yellow colors for higher PV cutoff lifetimes indicate that the PV cutoffs ~~stay~~ remain linked to the surface cyclones ~~for a few days, i.e. they remain linked and~~ and the two propagate and become older together. The transition to ~~beige/grey~~ blue colors along this diagonal shows that the number of these initial links decreases with time. A link disappears either because the PV cutoff decays, the surface cyclones decays, or the surface cyclone and the PV cutoff move away from each other. ~~The green/blue~~ As another example, the yellowish boxes in the lowermost row in Fig. **??**~~b indicate that many~~ e show that about 10% of the PV cutoffs with genesis ~~in the western North Atlantic are linked~~ over South Africa are related to surface cyclogenesis after a cutoff lifetime of 0.5~~-2 days. These links remain for a few days and then gradually disappear. These results show that most PV cutoffs with genesis over the western North Atlantic tend to be either linked to an 'old' surface cyclone at their genesis or be involved in cyclogenesis 1-2 days later. After about 2 days, almost 160 out of 206 PV cutoffs are linked to a surface cyclone (red curve) with the age of the surface cyclone ranging from 0 to more than~~ -1.5 days.

Cyclogenesis in the vicinity of the PV cutoff after up to 4 days ~~. In total 183 PV cutoffs in this region are linked to a surface cyclone at least once during their life cycle (number at top right in Fig. **??**b). Figure **??** shows that each region has its characteristic pattern. Half of the~~ lifetime occurs in all regions and can partly explain the increases or local peaks in the fraction of PV cutoffs linked to surface cyclones during their lifetime. In general, the preferred timing of PV cutoff life cycles and surface cyclone life cycles differs across regions. For example, over the Mediterranean, the most frequent scenario is that surface cyclones form between 0.5-1.5 days prior to PV ~~cutoffs forming over California (Fig. **??**a) are linked to a surface cyclone resulting in two peaks, one after about 1 day and one after 3 days: The first peak is the result of cyclogenesis ±1 day around PV~~ cutoff genesis and ~~the second one involves cyclogenesis after 2-3 dayslifetime. About 70% of PV cutoffs with genesis over the Mediterranean (Fig. **??**c) are linked to surface cyclones, often with cyclogenesis around 1 day prior to~~ remain linked to the PV cutoff for about 1-2 days. A similar scenario, but a bit an earlier cyclogenesis, occurs for PV cutoffs close to Antarctica. For cutoffs over the Nordic Seas, scenarios with cyclogenesis between about 2 days prior and 1.5 days after PV cutoff genesis ~~. Some PV cutoffs are also involved in cyclogenesis after 2-3 days lifetime. Only roughly a third of the~~ are all roughly equally frequent. And the most frequent scenario for PV cutoffs forming over ~~the eastern South Pacific are linked to surface cyclones during their life cycle (Fig. **??**d). The link preferentially occurs during the first 2 days~~ South Africa is cyclogenesis in the vicinity of the PV cutoff ~~life cycle and at or shortly after cyclogenesis. Over~~ between 0.5-1.5 days after

PV cutoff genesis. Hence, over South Africa, ~~almost 60%~~ cyclogenesis occurs as a concequence of the PV ~~cutoffs are linked to surface cyclones. Mostly,~~ cutoff, while over the Mediterranean and Antarctica, PV cutoff formation is rather the result of surface cyclogenesis and associated in-situ baroclinic development. The latter scenario is consistent with the classical picture of the ~~link first occurs at or shortly after cyclogenesis and after about 1 day cutoff lifetime. A rapid drop in the number of linkages occurs after about 2 days cutoff lifetime,which may be partially related to enhanced PV cutoff lysis rates around that time (as shown by the rapid drop of the green curve in Fig~~LC2 evolution and the composite of Type III cutoffs (Fig. **??**c,f), which shows a well developed surface cyclone at PV cutoff genesis [see also the case shown in the supplementary material Fig. S4]. But also secondary cyclogenesis ahead of an equatorward extended PV streamer forming downstream of an LC1 evolution and subsequent cyclonic break-up may result in a situation where PV cutoff genesis follows or co-occurs with surface cyclogenesis [as it can occur for Type II cutoffs, see Fig. **??**b,e and associated discussions and supplementary material Fig. S3]. ~~**??**e).~~

Also in JJA, the different regions show distinct characteristics (Fig. **??**). The relative frequency of PV cutoffs linked to a surface cyclone during the life cycle ranges between 8% over the central subtropical North Atlantic to 58% over the Hudson Bay. It is lowest for regions where Type I dominates and highest for regions where Type III dominates, consistent with the climatology of the three types. PV cutoffs ~~over Antarctica show a similar pattern as the ones over the western North Atlantic , although with a less clear second surface cyclone peak. Most often, PV cutoffs in this region are already initially~~ forming over the Mediterranean are substantially less frequently linked to surface cyclones ~~that formed roughly 1-2 days prior to PV cutoff genesis. Also in JJA , the different regions show distinct patterns (Fig.**??**). Many PV cutoff genesis events over Australia occur~~ in JJA compared to DJF, in agreement with the seasonality of the Mediterranean storm track (e.g., **?**). Surface cyclones linked to PV cutoffs over Australia frequently form almost simultaneously with ~~surface cyclogenesis (~~the PV cutoff [Fig. **??**f~~). This pattern is reminiscent of PV cutoffs over California and partially the Mediterranean, and South Africa in DJF. PV cutoffs over the central (eastern) subtropical North Atlantic (Fig. **??**b, c) are less frequently linked to surface cyclones . In the eastern subtropical North Atlantic, this linkage consists mainly of cyclogenesis after 1-3 days life time, reminiscent of South Africa in DJF. Over the Hudson Bay~~ , consistent with a Type II evolution and the example in this region shown in the supplementary material Fig. S3]. On the contrary, surface cyclones linked to PV cutoffs over the Hudson Bay and the Baltic Sea preferentially form up to several days prior to PV cutoff genesis (Fig. **??**~~a),PV cutoffs follow a similar pattern as over the western North Atlantic in DJF with many PV cutoffs that are early in their life cycle linked to surface cyclones with cyclogenesis a few daysprior to PV cutoff genesis. Also in this region, PV cutoffs can be additionally involved in surface cyclogenesis after 1-3 days~~ d,e) as it can be expected for a classical LC2 evolution that results in Type III cutoffs. In most regions, the fraction of PV cutoffs linked to a surface cyclone increases with the lifetime of the PV cutoffs during the first couple of days. Again, this can partly be linked to cyclogenesis in the vicinity of the PV cutoff after genesis, which occurs in most regions. But it can also occur that, after a couple of days, PV cutoffs meet a relatively old surface cyclone (as indicated by increases in the frequencies along a diagonal, e.g., around a t_{cutoff} of ~~their lifetime. Over~~ 4 days and a $t_{cyclone}$ of 1.5 days over the Baltic Sea~~and the Sea of Okhotsk, the patterns are less clear and more or less any kind of linkage to surface cyclones can occur.~~ , Fig. **??**e).

We conclude that there are general consistencies of the linkage between PV cutoffs and surface cyclones in the considered regions with archetypal baroclinic wave evolutions and the corresponding PV cutoff types. However, the wide range of combinations of PV cutoff lifetimes and cyclone lifetimes that can occur when the two systems meet shows that potentially complex evolutions take place. Further, the substantial differences between regions with the same dominant cutoff type show that specific local processes (such as, e.g., orographic influence on cyclogenesis) may play an important role.

5 ~~Discussion~~ Summary and Conclusions

In this study, a novel approach to identify and track PV cutoffs as three-dimensional objects was introduced and applied to ERA-interim reanalyses for the years ~~1979-2017~~1979-2018. This climatology of PV cutoffs is the first that comprises all near-tropopause cyclonic vortices, because it is global and independent of the selection of a vertical level. As the tracking is based on isentropic trajectories, it further allows quantifying ~~different processes during the PV cutoff life cycle (stratosphere-troposphere exchange, diabatic decay , reabsorption)~~diabatic decay and reabsorption. The resulting climatological dataset was used to study the life cycle of PV cutoffs in detail. In the following~~the main findings are summarized and compared to results from previous studies, starting with climatological frequencies and followed by the various investigated aspects of the life cycle. Based on these discussions, three archetypes~~ , a summary of the main results is given, separated into the three overarching findings, which are: (1) new insight into climatological occurrence and frequencies of decay and reabsorption, (2) a meaningful classification into three PV cutoff types, and (3) substantial regional variability of PV cutoff life cycles ~~are proposed~~and relevance of their vertical dimension. Finally, a brief outlook for further research is given. ~~Note again that, in this study, short lived (lifetime below 24 h) and shallow (isentropic thickness below 15 K during the whole life cycle) have not been considered.~~

5.1 ~~Climatological~~ New insight into climatological frequencies, decay, and ~~seasonal cycle~~reabsorption

Many of the presented frequency, genesis and lysis maxima of PV cutoffs are consistent with previous climatological studies~~.~~ ~~In the Southern Hemisphere, many frequency and genesis maxima agree well with~~ , but some previously unknown regions of occurrence are identified (e.g.~~?, ?, and ?. In the Northern Hemisphere, they compare favorably with ? mainly in subtropical latitudes, with e. g. ? in higher latitudes, and with ? in most regions if COLs at 500 hPa and 200 hPa are considered. However, in this study~~ , the circumpolar band around Antarctica). A main novelity of this study is that all of them are identified based on a consistent methodology and independent of the selection of a vertical level~~. Interestingly, the high PV cutoff frequencies reaching from California north-eastward across the US into the North Atlantic, in combination with the preferred movement of the California cutoffs along that band, agree very well with the frequencies and the movement of upper tropospheric storm track features identified by ?. A similar agreement occurs also for the enhanced frequencies over the North Pacific in DJF. Also, some of the identified maxima have not or only little been described in the literature before. In particular, the circumpolar band around Antarctica and the farequatorward reaching band in the South Pacific in DJF have not been documented as regions of COL occurrence yet. The circumpolar band around Antarctica and its seasonal change in symmetry agrees very well with the climatology of upper tropospheric storm track features discussed in ?. The maximum east of Brazil was mentioned only by ?. Our global analysis reveals also that the summer hemispheres have two preferred latitudes of PV cutoff occurrence. One in the~~

~~subtropics mostly in east- and poleward tilted bands over the Pacific and Atlantic, where frequent anticyclonic RWB is known to occur (e.g. **?**) and another one .~~, providing the most comprehensive climatological picture of PV cutoffs so far. It reveals that PV cutoffs in summer occur frequently over subtropical ocean basins equatorward of the jet stream, and at higher latitudes, in particular in the storm track regions ~~.~~poleward of the jet stream. In winter, PV cutoffs occur either poleward of the jet stream or, particularly frequently, in regions with split-jet conditions between the polar and subtropical jet streams.

~~In fact, some PV cutoff frequency maxima are in striking agreement with high cyclone frequencies. For example, the frequency maxima over the Canadian Arctic and south of Iceland in JJA agree particularly well with the surface cyclone maxima found by **?**. Frequency maxima over the southern Indian Ocean close to Antarctica in DJF also correspond well with surface cyclone maxima identified by **?**. Furthermore, a careful comparison to the climatology of jet streams (**?**) reveals that high PV cutoff frequencies occur often slightly poleward of jet frequency maxima (western North Atlantic, Japan, around Antarctica in DJF) and sometimes poleward of the subtropical jet maxima and equatorward of the polar jet maxima (Mediterranean and central Europe in DJF, Australia in JJA). But PV cutoffs are also frequent in regions where strong jet streams are absent, in particular over the subtropical ocean basins in summer. A particularly interesting geographical pattern was also found for PV cutoff lysis frequencies. In summer, lysis frequencies are enhanced over the eastern parts of the land masses, while in winter they are largest over the western parts of the land masses and the eastern parts of the ocean basins. This is also in agreement with the geographical distribution of enhanced negative cross-tropopause mass fluxes. COL lysis rates as identified by **?** show a similar qualitative seasonal pattern . This indicates that in summer, PV cutoffs decay mainly due to orographic effects (~~Further, the first climatological quantification of diabatic decay and reabsorption revealed that both scenarios occur equally frequently, in contrast to the prevailing opinion that diabatic decay dominates. While decay tends to occur on lower isentropic levels, reabsorption is more frequent on higher isentopic levels. In addition, we found that the two scenarios have distinct geographical patterns of occurrence. This novel analysis sheds new light into a fundamental aspect of dynamical meteorology. In addition, the frequent occurrence of reabsorption may be relevant for midlatitude predictability, because it is a nonlinear interaction of the PV cutoff and the PV waveguide that potentially results in large uncertainties in the Rossby wave pattern (see, e.g.~~friction, orographic convection)and continental convection, and in winter enhanced diabatic activity related to warm ocean surfaces is more important. The modelling study of **?** supports this hypothesis: They showed that continental convection related to orography was crucial for the decay of a COL over the Andes in March 2005.~~, **?**).

5.2 Meaningful classification into three PV cutoff types

Following **?** and **?** we classified PV cutoffs according to their position relative to the jet stream (Type I: equatorward, Type II: between two-jets, Type III: poleward). We argue that such a classification is meaningful from both a fundamental atmospheric dynamics as well as from a predictability and impacts perspective. The main characteristics of the three types are summarized in Table **??**.

~~Several previous studies found a clear seasonal cycle with about four times more COLs forming in summer than in winter for both hemispheres but also that it depends strongly on the considered pressure level (**???**). The seasonal cycle in this study is much weaker, in agreement with the findings of **?**, if they took into account all isentropic levels from 305-370 K. Hence, its~~

~~seems that the strong seasonal cycle found in previous studies is mainly related to the seasonal cycle of the vertical (pressure or isentropic) level on which they occur, rather than a seasonal cycle in the frequency of PV cutoff / COL formation for illustration of this aspect, see ?, their Figure 8b.~~

5.3 ~~PV cutoff life cycles~~

~~Subsets of PV cutoff tracks were selected based on twelve different genesis regions and their life cycle was studied in detail. It was found that a characteristic difference between PV cutoffs in different genesis regions is the genesis mechanism: PV cutoff genesis occurs either as anticyclonic RWB equatorward of~~ From a fundamental atmospheric dynamics perspective, the results show that PV cutoff life cycles can be linked to the well-established archetypes of baroclinic wave life cycles and Rossby wave breaking. Type I forms in the subtropics from anticyclonic Rossby wave breaking and can be regarded as the result of an LC1 type evolution. Type III forms mainly in the storm track regions from cyclonic RWB, which is consistent with an LC2 type evolution. Finally, Type II forms in subtropics and mid-latitudes and, similarly to Type I, from anticyclonic RWB. But, on the contrary to Type I, it forms in an area with cyclonic barotropic shear equatorward of a (subtropical) jet stream, ~~anticyclonic RWB followed by cyclonic RWB between the polar and the subtropical jets, or cyclonic RWB poleward of the jet stream. The life cycle analysis provided novel insight into the mobility, life times, and vertical extent~~ which counteracts the anticyclonic tilt and can result in a cyclonic break up of the PV streamer. While pointing out these consistent dynamical scenarios, we also recognize the large variablity within each type and that individual evolutions may substantially differ from these archetypes. Nonetheless, the classification may provide helpful guidance to study the predictability and surface impacts of PV cutoffs. ~~First, PV cutoffs can be very mobile in many regions. Hence,~~ It stresses that particular attention should be given to Type II cutoffs, because of their potentially substantial impact on surface cyclogenesis and precipitation and their frequent occurrence in populated areas. In addition, given the different dynamical situations that lead to the formation of the three types, substantial differences in the processes influencing their predictability can be expected. For example, for Type III, errors in the ~~picture that PV cutoffs are mainly quasi-stationary systems is misleading. In fact, many PV cutoffs travel several thousand kilometers. This result stands in contrast to studies pointing out the quasi-stationarity of COLs (e.g. ??) or even assume it to justify assumptions for the tracking procedure (e. g. ?). Then, median life times can be highly variable between regions and range from two days over South Africa to six days over the central subtropical North Atlantic. The frequent occurrence of PV cutoffs with long life times (larger than three days) is inagreement with ?, who found mean life times of 6-8 days in large parts of the Southern Hemisphere, but is in contrast to other studies, that found that a vast majority of COLs have life times shorter than three days (~~surface cyclogenesis process prior to PV cutoff genesis may be a major driver of errors related to the PV cutoff. Such an influence is not expected for Type I, because they are rarely close to surface cyclones. On the contrary, errors related to anticyclonic RWB and/or the upstream surface cyclone might be particularly relevant for errors related to Type I and II cutoffs [similar to the cases discussed in, e.g.~~???). These differences in mobility and life time most likely arise from the different identification and tracking methods. The 3D approach used in this study is expected to result in longer lifetimes and larger travel distances than approaches based on single levels~~, ? and ?].

5.3 Substantial regional variability of PV cutoff life cycles and relevance of their vertical dimension

In the second part, subsets of PV cutoff tracks were selected based on twelve different genesis regions and their tracks, vertical evolution, decay and reabsorption, and the link to surface cyclones were studied in detail.

~~We~~ A particularly novel aspect was a composite analysis of the vertical evolution of PV cutoffs along the life cycle, which highlighted the relevance of the vertical dimension when investigating PV cutoffs~~(see Figs. ?? and ??).~~ . It showed that PV cutoffs can extend over many isentropic levels and in different regions ~~show~~ exhibit different climatological vertical 'footprints' during their life ~~cycle~~cycles. While some tend to rise to higher levels, others tend to sink to lower levels. Remarkably consistent across regions is the average duration of about one day until the climatological maximum vertical extent is reached, i.e., until the full three-dimensional break-up process is completed after PV cutoff genesis.

These vertical footprints of PV cutoffs are modulated by the appearence and disappearance of PV cutoffs on single isentropic levels. ~~Disappearence on an isentropic level occurs via diabatic decay or reabsorption. For the first time, it was quantified how frequently PV cutoffs decay diabatically or are reabsorbed by the stratospheric reservoir when they disappear at an isentropic level. Results showed that reabsorption is as frequent as decay and occurs on higher isentropic levels for 2D PV cutoffs with higher PV and a larger area. Diabatic decay is the main reason why in many regions PV cutoffs tend to disappear with time at lower levels. Interestingly, the relative frequency of diabatic decay and reabsorption~~ The relative frequency with which a PV cutoff undergoes diabatic decay or reabsorption during its life cycle varies greatly between regions. Interestingly, in some regions, these frequencies are substantially different from the climatological frequencies of the dominant PV cutoff type in the respective region. This demonstrates that the probability for a PV cutoff to experience diabatic decay or reabsorption can be strongly influenced by specific regional characteristics.

On the contrary, it is found that the expected lifetimes are relatively similar across most regions, with the notable exception of PV cutoffs forming over the cental subtropical North Atlantic, ~~resulting in distinct vertical evolutions and different life times. For example, during the life cycle of PV cutoffs with genesis over the eastern South Pacific diabatic decay is 60% more frequent than reabsorption, while over Antarctica reabsorption is almost twice as frequent as diabatic decay. Decay and reabsorption both occur preferrentially towards the end of a (3D) PV cutoff life cycle. The geographical distribution showed that lysis maxima in higher (lower) latitudes are generally dominated by reabsorption (decay). Decay and reabsorption are also particularly frequent in the subtropical bands with high PV cutoff frequencies in the summer (especially over the North Atlantic and North Pacific) where lysis is not particularly frequent. This is most likely the result of frequent transient decay /reabsorption events associated to the long-lived and quasi-stationary PV cutoffs in this region~~which persist on average more than twice as long as in most other considered regions.

~~While diabatic decay is already an indication of high STT activity, in this study, STT and TST were specifically quantified during the whole life cycle of the PV cutoffs. It was found that STT dominates over TST for PV cutoffs in the global average and for many investigated genesis regions, which is well in agreement with previous studies (e.g ??). Despite the various differences in the methodologies, the magnitude of STT and TST mass fluxes found in this study is comparable to the magnitudes found by other studies investigating similar systems, when the different residence times are taken into account for the Lagrangian-based~~

~~diagnostics. For example, **?** found values of up to 10000 kg km^{-2}s^{-1} for STT and up to 3000 kg km^{-2}s^{-1} for TST within a PV cutoff over the Mediterranean using a residence time of 12 h. For intense North Atlanticcyclones in DJF, **?** found average STT (TST) values between 500-1000 kg km^{-2}s^{-1} (300-500 kg km^{-2}s^{-1}) for a 48 h residence time. Using a Eulerian diagnostic, **?** found an average STT flux of about 2100 kg km^{-2}s^{-1} over four days associated to a tropopause fold in a PV cutoff over the Southern US. As a novel finding, TST balances or even dominates over STT for PV cutoffs over the subtropical ocean basins in summer and over polar regions, meaning that PV cutoffs in these regions tend to grow rather than decay by diabatic processes. PV cutoffs in regions where TST dominates over or at least balances STT are more likely to end their life cycle with reabsorption than with diabatic decay. In most regions, TST tends to decrease with lifetime and the net fluxes are strongly determined by the evolution of STT. STT is often particularly large towards the end of the life cycle and in some regions it is also large initially and follows a u-shaped evolution.Finally, as a step towards using the PV cutoff climatology to study their surface impacts, the chronology of the linkage between PV cutoffs and surface cyclones was investigated. A first conclusion was~~ Considering the link to surface cyclones we found that the frequency with which a PV cutoff is linked to a surface cyclone during its life cycle strongly depends on the region ~~. While in the storm track regions, most PV cutoffs are linked to surface cyclones, PV cutoffs in subtropical regions are so less frequently~~and that these differences cannot only be explained with the climatological differences between the cutoff types, additionally suggesting that regional aspects matter. By analyzing the frequencies of the possible combinations of PV cutoff ~~life times and life times~~ lifetimes and lifetimes of the linked surface cyclones, it was found that most regions have ~~different~~ certain combinations that preferentially occur. ~~PV cutoffscan be linked to surface cyclones that formed~~ In regions with many Type II and III cutoffs, surface cyclones frequently form at or up to a few days ~~before~~ prior to PV cutoff genesis~~but also, as~~, consistent with the archetypal evolutions associated to these two PV cutoff types. As an important novel finding, they are frequently involved in surface cyclogenesis up to several days after they have formed. This highlights that, while PV cutoffs have mostly been considered as weather systems at the end of a baroclinic life cycle, they can also be initiators of new baroclinic life cycles.

5.4 ~~Three archetypes of~~ Outlook

The tracking methodology and the PV cutoff ~~life cyclesSome of the properties of PV cutoff life cycles discussed in the previous section show remarkable similarities among different regions. In the first place, this is true for the three identified genesis mechanisms, which are directly linked to the position of PV cutoff genesis relative to the jet stream(s). As identified in this study , PV cutoffs with similar genesis regions, i.e. mechanisms, also exhibit similarities regarding other dynamical aspects of their life cycle. This suggests that different types of PV cutoff life cycles exist. While such classifications have been proposed and modified for extratropical cyclones since **?**, a classification of the life cycles of upper-level closed cyclones based on dynamical or physical properties is almost inexistent. A first step into this direction was already made by **?**, who separated COLs into four types according to the geometry of the associated upper-level flow field their Fig. 10.4. A separation of closed cyclones at 500 hPa according to their relative position to the jet stream has already been performed by **?**, but mainly because of practical reasons rather than dynamical or physical differences. **?** separated COLs into three types, depending if they were~~

~~located within equatorward extensions of the subtropical jet (subtropical type COL), the polar jet (polar type COL), well poleward of the polar jet (polar vortex type COL). Thereafter, the development of COL classifications has ceased. However, we consider such a classification essential to further improve the understanding of PV cutoff / COL life cycles and their regional variability. Here, a classification into three archetypal PV cutoff life cycles is proposed that is, on the one hand, to some extent in line with the previous classifications using criteria like the jet-relative position (**??**) or the shape of the wave breaking (**?**), and, on the other hand, includes additionally various dynamical and physical aspects of their life cycles. The main characteristics of these types are described in Table **??** and are in the following briefly summarized.~~

– ~~Type I (*anticyclonic*) PV cutoffs (central and eastern subtropical North Atlantic, eastern South Pacific, South Africa) form equatorward of the jet stream by anticyclonic RWB most frequently over subtropical ocean basins in summer and are not very frequently associated to surface cyclones. These PV cutoffs in the subtropical ocean basins are characterized by positive net cross-tropopause mass fluxes, resulting in a downward growth of the PV cutoffs as long as they remain over this area. If they form in the eastern part of the ocean basins, they can easily get under the influence of eastward motion, resulting in their rapid decay as they are advected over land. During such rather short life cycles, they are sometimes involved in surface cyclogenesis. If they form in the central and western parts, they may remain stationary or even move westward and can have very long life times. The final phase of Type I PV cutoffs often involves enhanced STT, and diabatic decay is generally more frequent than reabsorption, in particular for PV cutoffs over South Africa and the eastern South Pacific.~~

– ~~Type II (*between-jets*) PV cutoffs (California, Mediterranean, Baltic Sea, Australia) form between the polar andsubtropical jet streams by anticyclonic RWB equatorward of the polar jet followed by a cyclonic break-up poleward of the subtropical jet. They are often associated to surface cyclones with genesis shortly before or at PV cutoff genesis. Already initially STT dominates over TST and frequent diabatic decay occurs at lower levels. STT tends to follow a u-shaped evolution with the highest values at the beginning and the end of the life cycle. Diabatic decay is frequent during all phases of the life cycle, increasing towards the end and in some cases at the beginning. While diabatic decay is more frequent than reabsorption during most of the life cycle, reabsorbtion and decay are roughly equally important or reabsorption even dominates in the final phase of Type II PV cutoffs. This is likely the case because, as they experience diabatic erosion, they approach the stratospheric reservoir and frequently a remnant of the PV cutoff is reabsorbed before it can decay completely.~~

– ~~Type III (*cyclonic*) PV cutoffs (western North Atlantic, Antarctica, Hudson Bay) form poleward of the jet stream by cyclonic RWB in the storm track regions. At their genesis, they are typically associated to surface cyclones that formed 1-3 days earlier, but can also be involved in cyclogenesis after a few days life time. STT and TST are roughly equal during the whole life cycle, while one of the two tends to be slightly larger, depending on the region (see western North Atlantic vs. Antarctica). These differences may be associated to the generally moister and warmer atmospheric conditions over the western North Atlantic than over the Southern Ocean. As a result of the quasi-balance between STT and TST, diabatic decay is infrequent during the whole life cycle and their three-dimensional evolution is "quasi-adiabatic", i.e. not much~~

~~vertical displacement occurs. Again PV cutoffs over the western North Atlantic are an exception where diabatic decay is frequent. Type III PV cutoffs end their life cycle preferentially by reabsorption.~~

~~These types are of course rough classifications and, in reality, individual PV cutoffs may undergo a mixture thereof. PV cutoffs over the Sea of Okhotsk could not be attributed clearly to one life cycle type but rater feature a mixture of Types II and III. Despite these limitations, the proposed types may serve to better compare and contrast the highly varying evolutions of~~ climatology presented in this study open various opportunities for further research on this relevant flow feature. A major advantage is that they can be used for global studies, regional studies, and, as a particular asset, studies to compare PV cutoffs in different regions~~of the globe.The supplementary material S3 (Figures S1-S3) illustrates example cases for each of the three types. It remains a challenge for future research to identify the underlying dynamical and thermodynamical mechanisms responsible for the major differences between the three life cycle types.~~ .

5.5 ~~Outlook~~

~~The PV cutoff climatology presented in this study opens various opportunities for further research on this relevant flow feature.~~ An interesting open question ~~directly emerging from this study~~ that can be adressed with the present dataset is for example how many of the identified surface cyclogenesis events linked to a PV cutoff can be reasonably explained by the dynamical forcing of the PV cutoff and how this aspect compares across regions and/or PV cutoff types. An aspect that we will address in a forthcoming study is the role of PV cutoffs for (extreme) precipitation ~~and surface cyclones/cyclogenesis~~ on a global scale. A related topic may be to quantify trends in PV cutoff frequencies and the link to precipitation trends [as for example investigated for Australia by **?**]. This would potentially contribute to the discussion about the role of dynamic and thermodynamic drivers of precipitation changes (e.g., **?**). Also, the role of particularly long-lived subtropical PV cutoffs (e.g., over the central subtropical North Atlantic) for the export of tropical moisture into the mid-latitudes and subsequent heavy precipitation events [as shown by **?** for a case study] could be investigated. ~~A potential link to the ocean circulation~~
Applying the presented methodology to other datasets even opens doors to answering further relevant questions. For example, using climate model simulations it could be studied ~~by focusing on the frequent diabatic decay events and strongly negative net cross-tropopause mass fluxes in the regions of the western boundary currents. Finally, it is an open question if and~~ how the ~~diabatic modification and therefore the life cycle~~ life cycles of PV cutoffs change under global warming. As it considers the full three-dimensional evolution of PV cutoffs, the methodology is also particularly useful to study errors and uncertainty in the structure and evolution of PV cutoffs ~~changes under global warming~~in operational weather forecasts.

Data availability. All data is available from the authors upon request.

Author contributions. RP prepared all analyses and the manuscript. HW provided scientific advice throughout the whole project, helped setting up the tracking algorithm, and provided valuable suggestions for improving the manuscript. MS provided technical support and guidance throughout the whole project and provided valuable inputs that helped improving the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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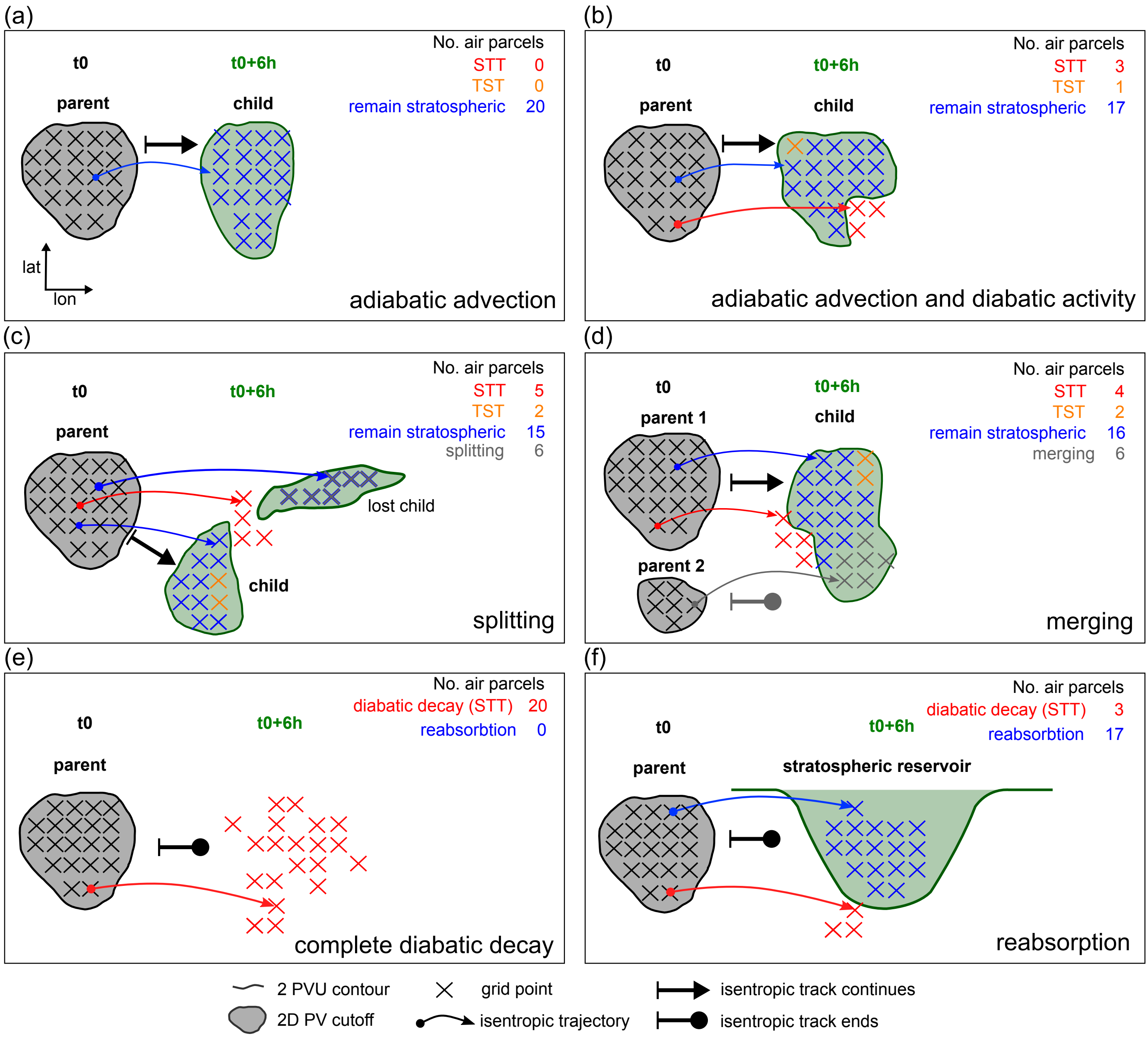

Figure 1. Schematic visualisation of the tracking methodology and the associated quantification of STT, TST, diabatic decay, and reabsorption on an isentropic surface in longitude-latitude space for situations with (a) perfect adiabatic advection of the PV cutoff, (b) adiabatic advection and the presence of diabatic processes (c) the same as (b) but with splitting, (d) the same as (b) but with merging, (e) complete diabatic decay, and (f) reabsorption with little diabatic decay. See text for a detailed discussion.

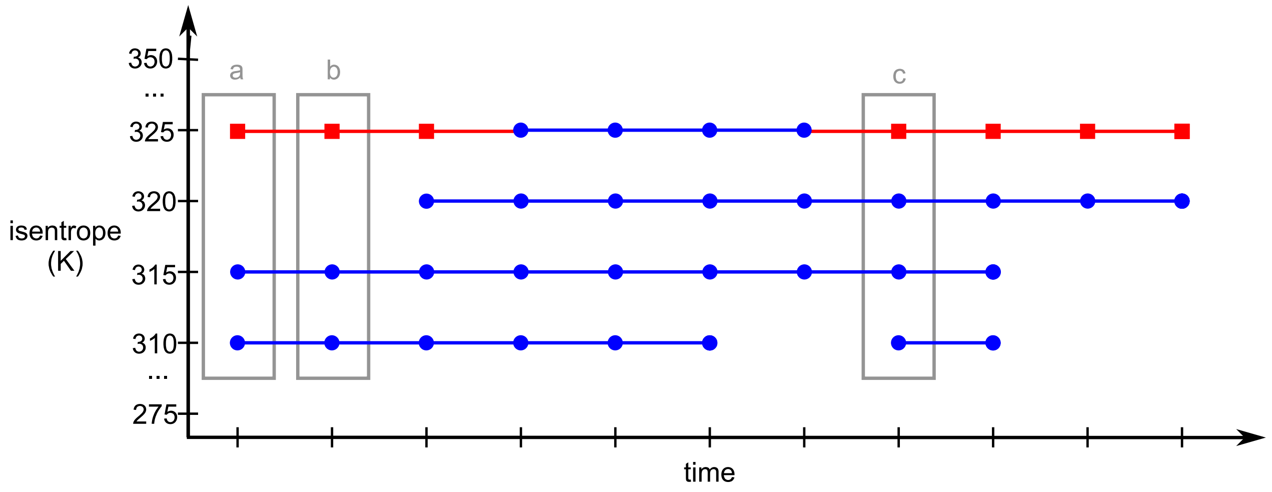

Figure 2. Schematic visualization of the construction of a 3D PV cutoff track from all overlapping isentropic 2D PV cutoff tracks. Isentropic 2D tracks making up the final 3D track are marked with blue lines and dots, and the isentropic tracks that are removed with red lines and squares. See text for a detailed discussion.

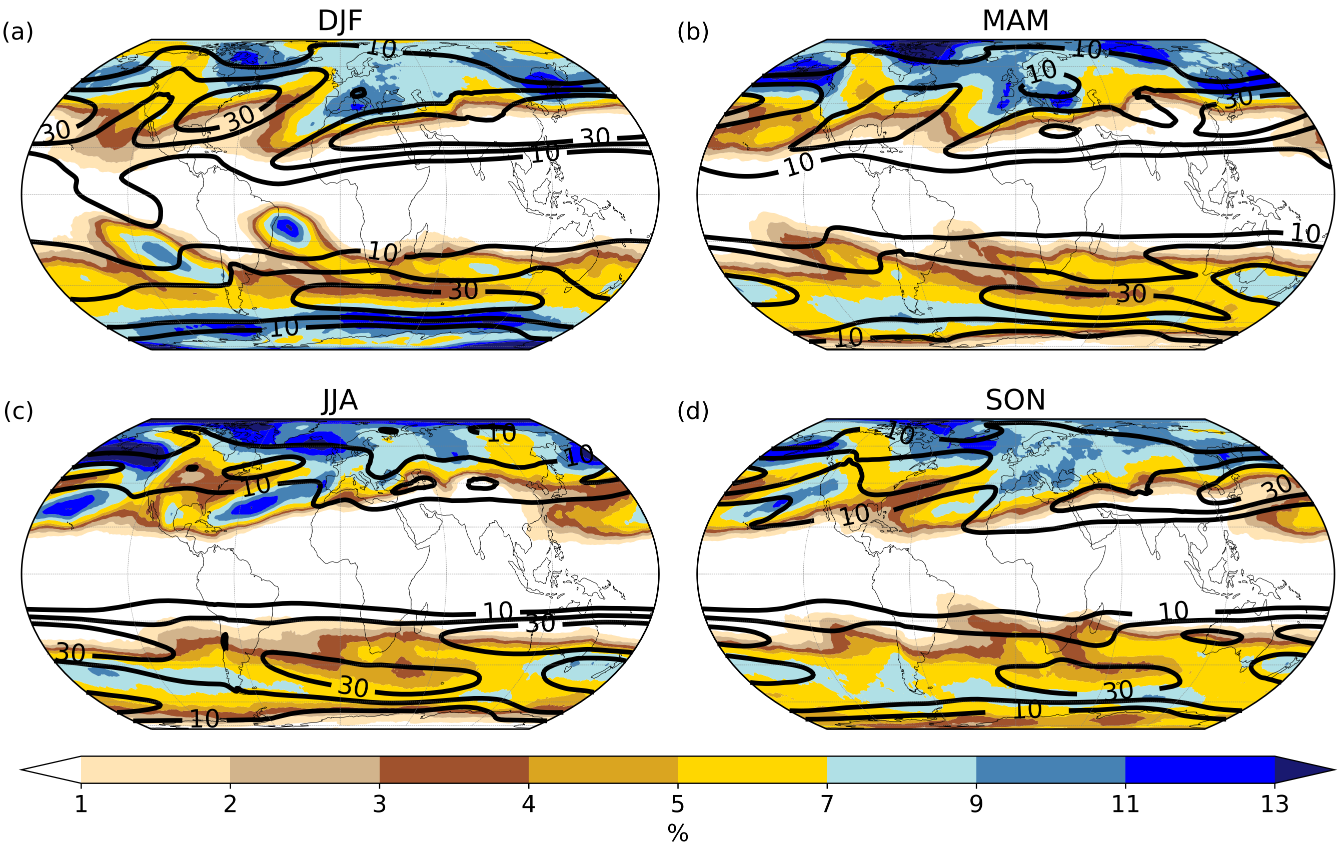

Figure 3. Seasonally averaged PV cutoff frequencies (shading, in %) and zonal wind speed (thick black line, 10, 20, and $30\,\mathrm{m\,s^{-1}}$) for (a) DJF, (b) MAM, (c) JJA, and (d) SON~~during the period 1979-2017~~.

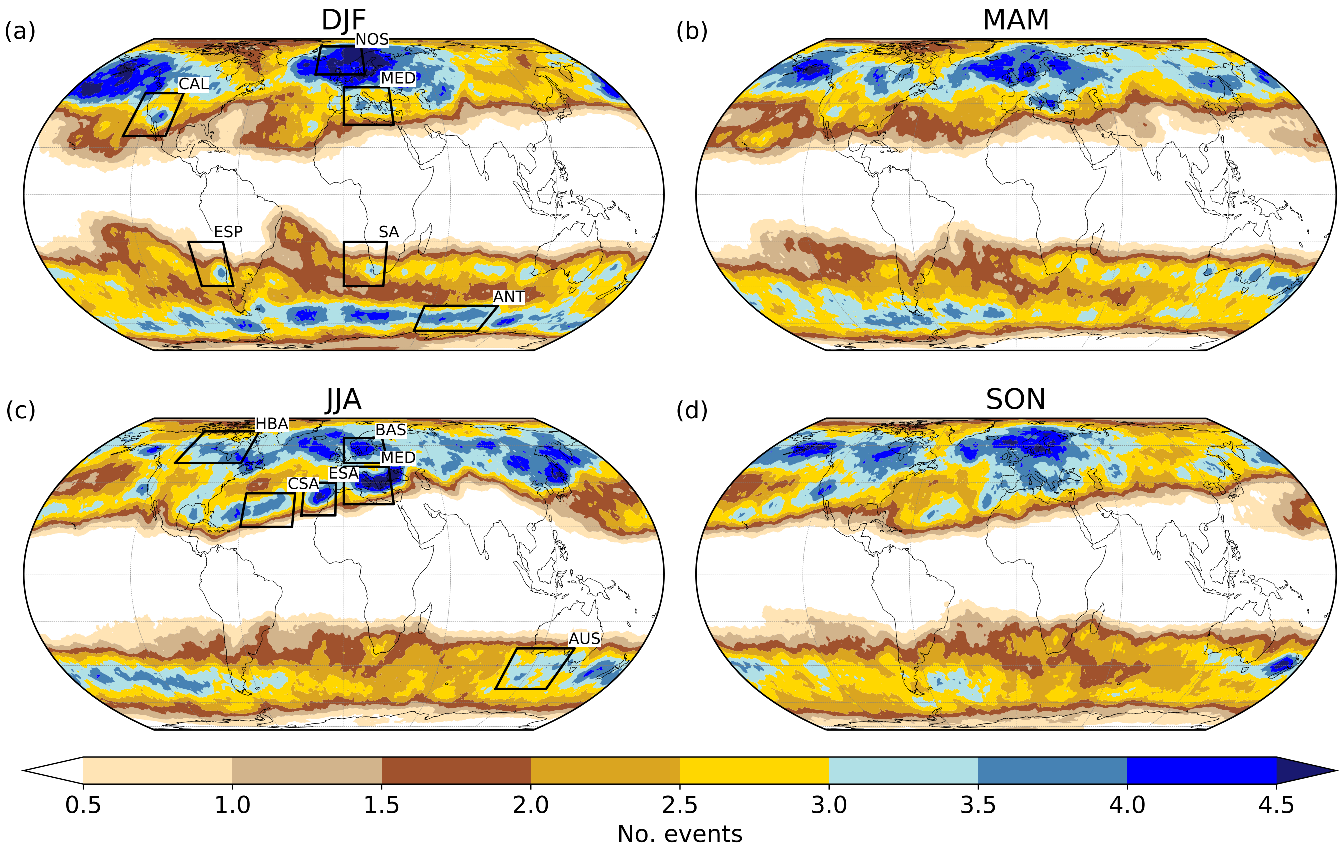

Figure 4. Seasonal average number of PV cutoff genesis events within a distance of 500 km in (a) DJF, (b) MAM, (c) JJA, and (d) SON~~during the period 1979-2017~~. The location of a genesis event is determined by the centre of the first PV cutoff of a track. Black boxes mark the genesis regions investigated in Sect. **??**.

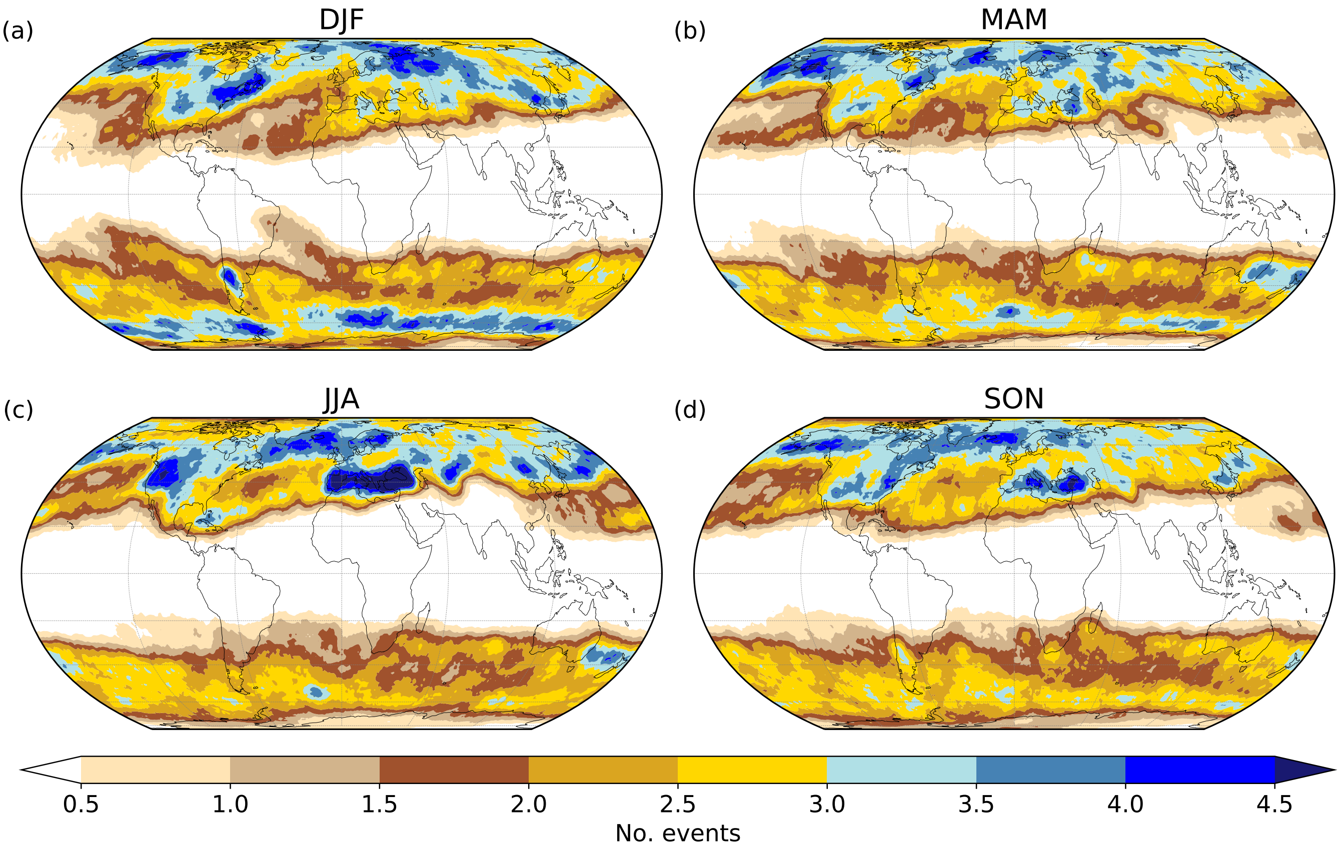

Figure 5. Seasonal average number of PV cutoff lysis events within a distance of 500 km in (a) DJF, (b) MAM, (c) JJA, and (d) SON~~during the period 1979-2017~~. The location of a lysis event is determined by the centre of the last PV cutoff of a track.

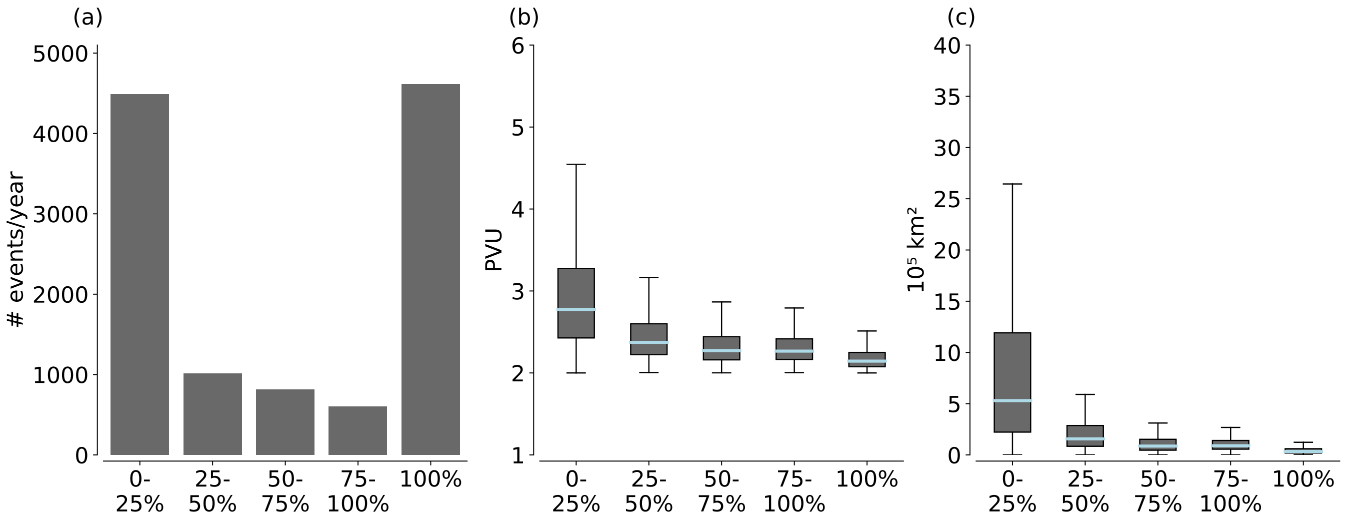

Figure 6. (a) Histogram of the percentage of air parcels in a PV cutoff experiencing decay whenever the PV cutoffs disappears on an individual isentrope (average annual number of events, 0% corresponds to pure reabsorption, 100% to complete diabatic decay), and (b,c) standard box plots (outliers not shown) of (b) mean PV and (c) area of the PV cutoff at the isentropic level from which it disappears for the histogram classes in (a).

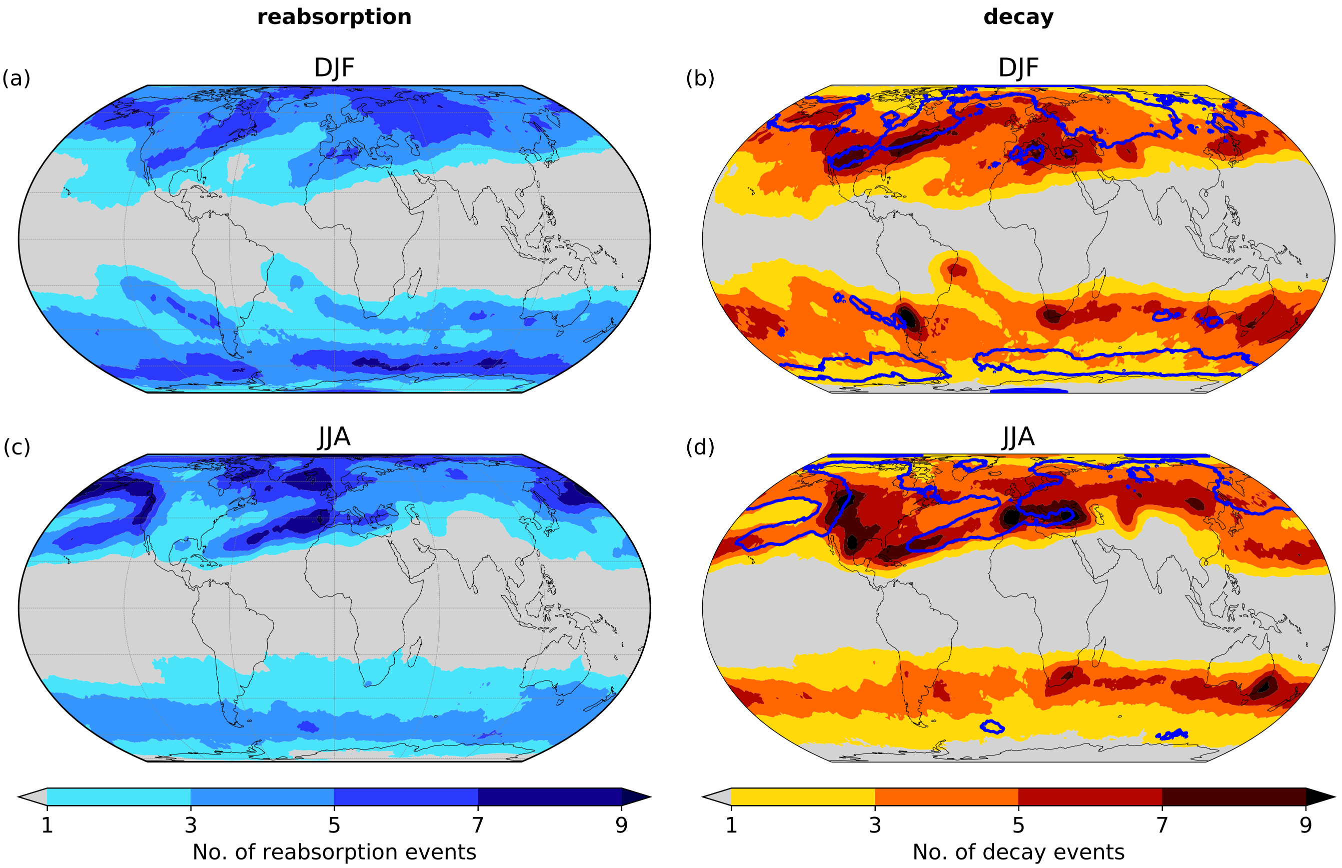

Figure 7. Average number of (a,c) reabsorption (less than 50% decay, blue shading) and (b,d) diabatic decay (more than 50% decay, red shading) events per season within a distance of 500 km for (a,b) DJF and (c,d) JJA. As reference, the contour for five reabsorption events per season (blue contour) is shown in panels (b,d).

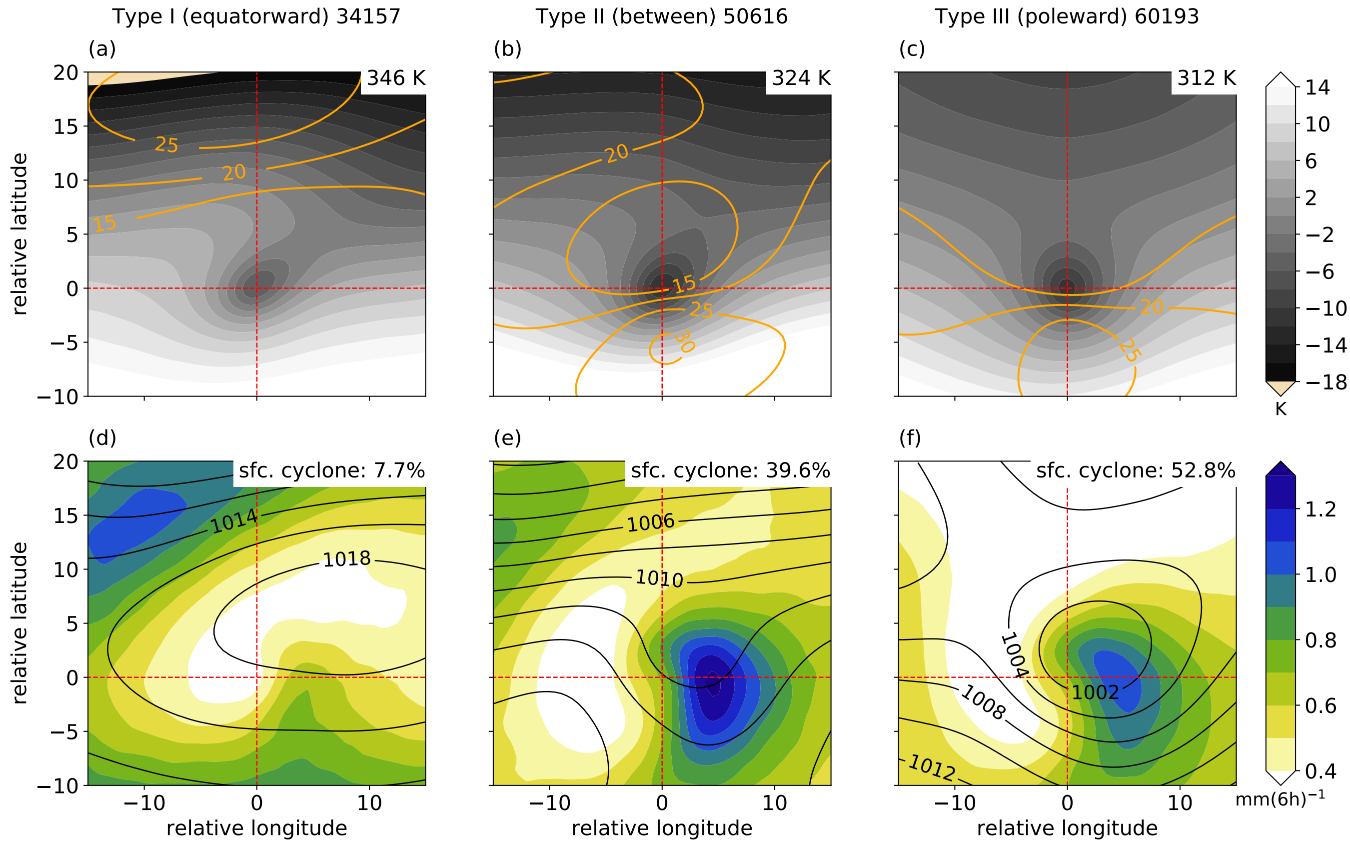

Figure 8. ~~Synoptic~~ Cutoff-centered composites ~~during PV cutoff genesis in DJF in the regions:~~ of (~~a~~a-c) ~~California,~~ equivalent potential temperature at the 2 PVU isosurface (~~b) western North Atlantic~~shading, ~~(c) Mediterranean~~in K, ~~(d~~given as difference from the domain mean value indicated at the top right of each panel) ~~eastern South Pacific, (e) South Africa,~~ and ~~(f) Antarctica. Shown are sea level pressure (grey contours, every 4 hPa),~~ zonal wind speed at ~~250~~300 hPa (~~black~~ orange contours, ~~30 and 40 m s~~in m s^{-1}), ~~anomaly of geopotential height at 250 hPa~~ and (d-e) total precipitation (shading, in ~~gpdm~~mm(6 h)~~,~~$^{-1}$) and ~~frequencies of stratospheric PV streamers~~ sea level pressure (~~yellow~~black contours, ~~50 and 70%~~in hPa) ~~, tropospheric~~ at PV ~~streamers~~ cutoff genesis, individually for (~~cyan~~a,~~50 and 70%~~d) Type I, ~~cyclones~~ (~~green shading~~b,~~30 and 50%~~e) Type II, ~~dashed~~ and (~~dotted~~c,f) ~~if more than 5% higher~~ Type III. The total number of tracks of each type is indicated at the top of panels (~~lower~~a-c)~~than climatology~~. Additonally, the percentage of PV cutoffs linked to a surface cyclone during their life cycle is indicated for each type at the top right of panels (d-f).

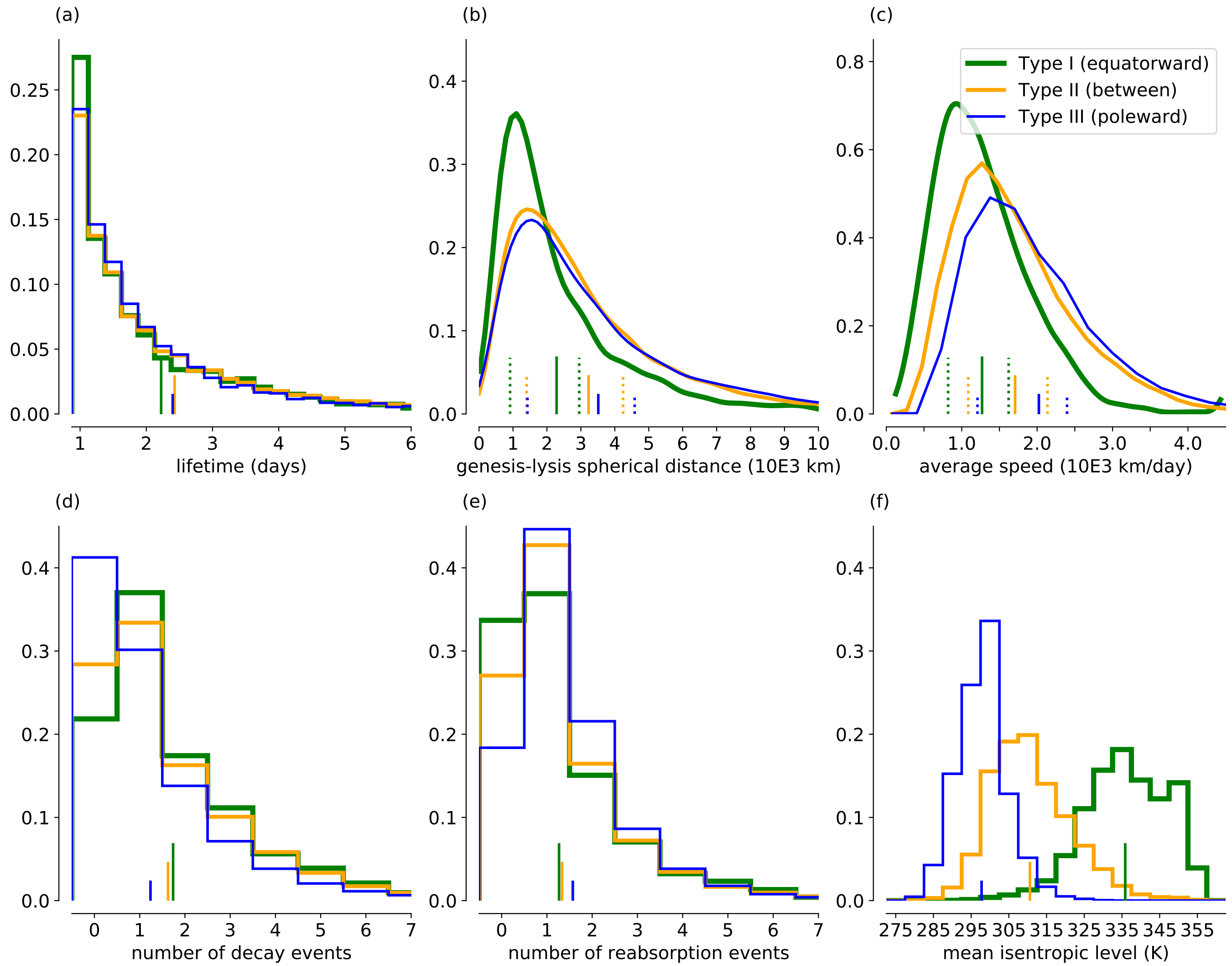

Figure 9. ~~Same as Fig. ?? but for PV cutoff genesis in JJA in the regions~~ Empirical distributions of (a) ~~Hudson Bay~~lifetime, (b) ~~central subtropical North Atlantic~~spherical distance between genesis and lysis locations, (c) ~~eastern subtropical North Atlantic~~average propagation speed, (d) ~~Baltic Sea~~number of decay events, (e) ~~Sea~~ number of ~~Okhotsk~~reabsorption events, and (f) ~~Australia~~the mean isentropic level during the life cycle PV cutoffs of Types I, II and III. For ~~all regions in~~ (a,d,e,f) distributions are shown as normalized histograms with the ~~Northern Hemisphere~~bar widths corresponding to unity, ~~an additional contour of wind speed at 250 hPa~~ i.e., the vertical axis values can be read as percentages, and for (~~20 m s^{-1}~~b,~~black contour~~c) ~~is~~ distributions are shown as density estimates. Vertical lines indicate (solid) mean values and (dashed) upper and lower quartiles.

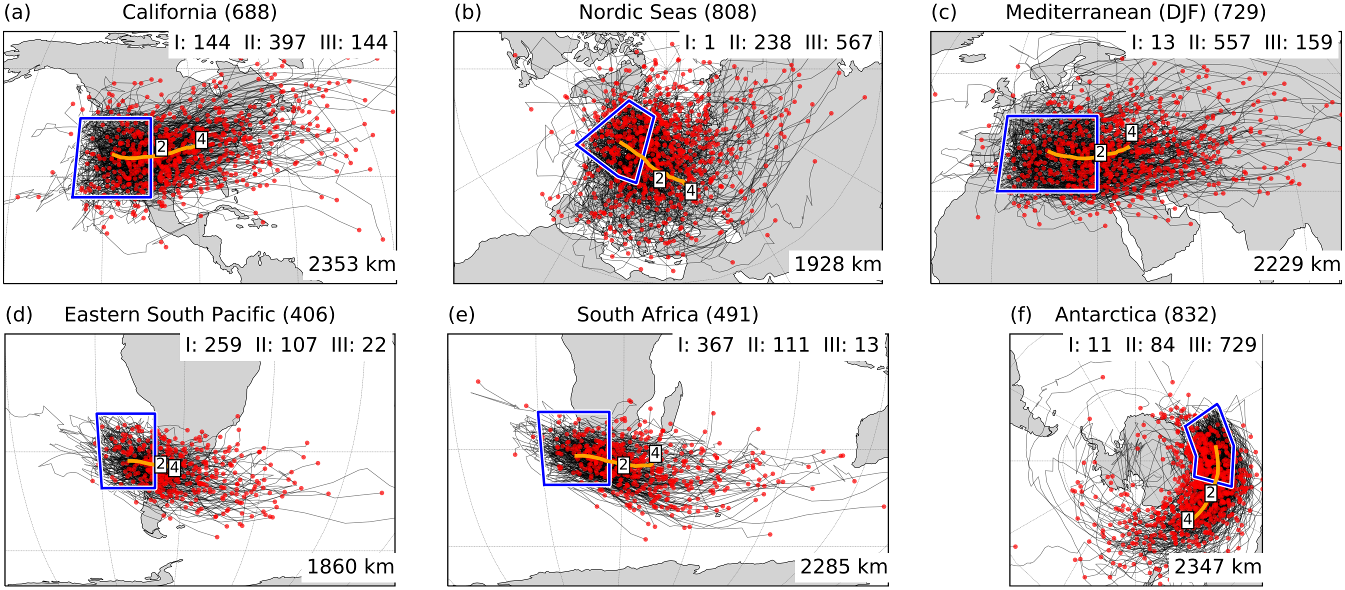

Figure 10. ~~Tracks~~ All tracks (black lines)~~and~~, lysis points (red dots), and average tracks (orange lines, including average location at days 2 and 4) of PV cutoffs with genesis over the six selected regions (blue boxes) in DJF: (a) California, (b) ~~western North Atlantic~~Nordic Seas, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica. The average spherical distance between genesis and lysis is indicated at the bottom right of each panel.

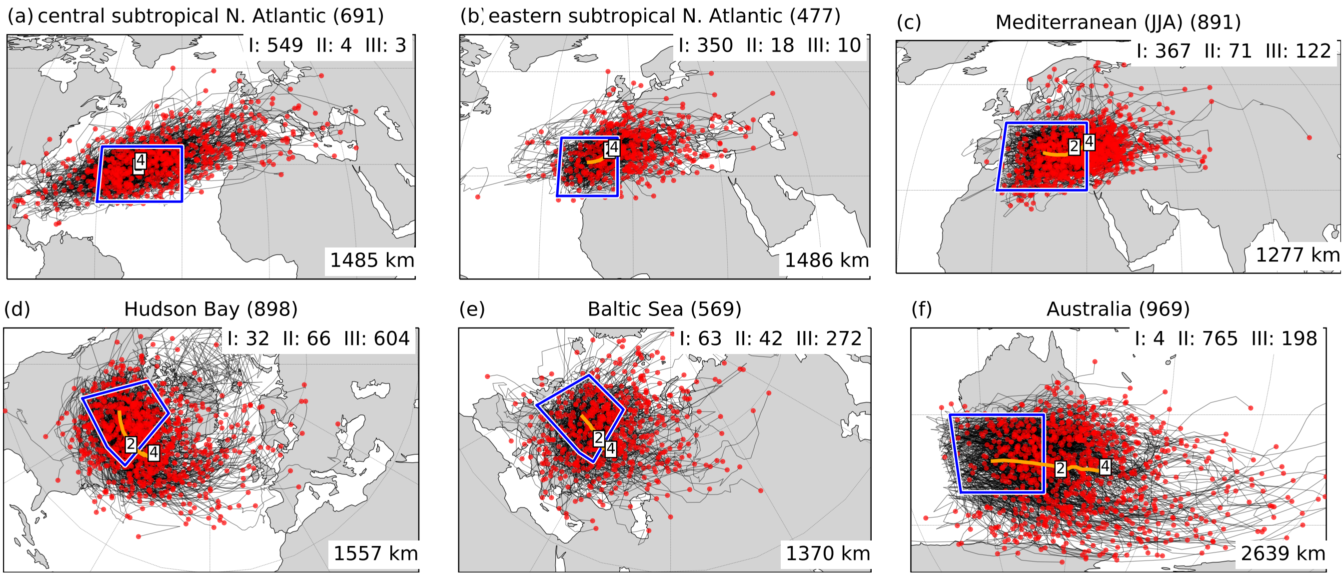

Figure 11. Same as Fig. **??** but for JJA and (a) ~~Hudson Bay, (b)~~ central subtropical North Atlantic, (~~e~~b) eastern subtropical North Atlantic, (c) Mediterranean, (d) ~~Baltic Sea~~Hudson Bay, (e) Baltic Sea~~of Okhotsk~~, and (f) Australia.

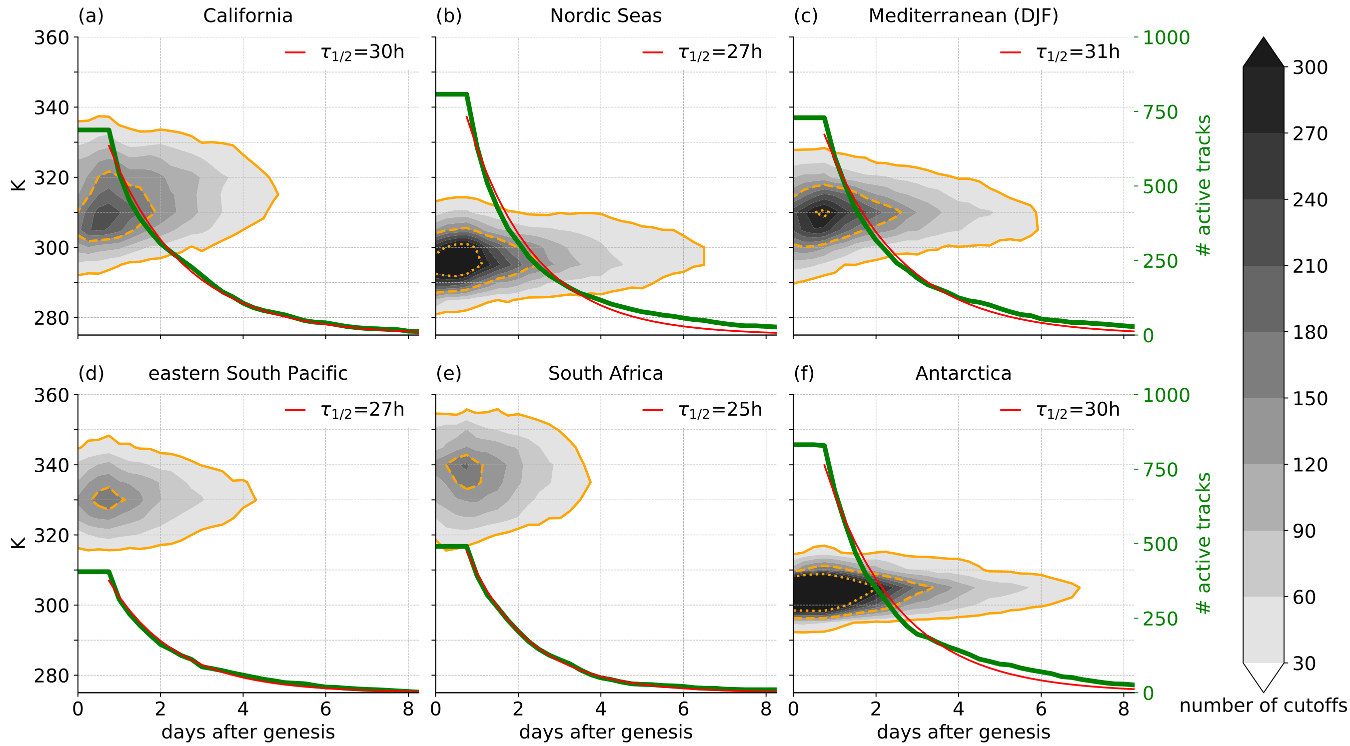

Figure 12. Number of PV cutoffs present on all isentropic levels (shading) and total number of active cutoff tracks (green curve) and an exponential function fitted to the number of active tracks after a lifetime of one day (red curve) as a function of lifetime for PV cutoffs with genesis over the six selected regions in DJF: (a) California, (b) ~~western North Atlantic~~Nordic Seas, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica. Values in the upper right corners correspond to PV cutoff half lifes. Orange contours mark frequencies of (solid) 30, (dashed) 150, and (dotted) 300 cutoffs.

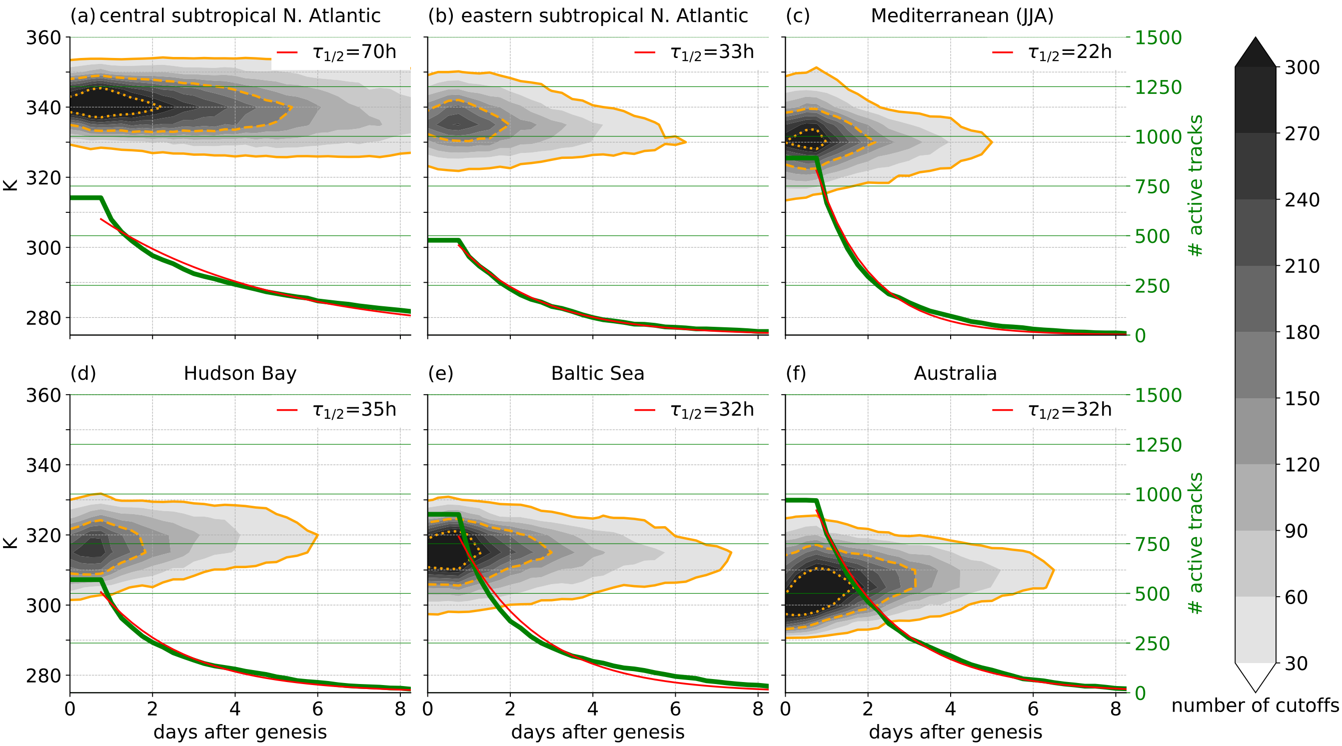

Figure 13. Same as Fig **??** but for JJA and (a) ~~Hudson Bay, (b)~~ central subtropical North Atlantic, (~~e~~b) eastern subtropical North Atlantic, (c) Mediterranean, (d) ~~Baltic Sea~~Hudson Bay, (e) Baltic Sea~~of Okhotsk~~, and (f) Australia.

~~(a) Histogram of the percentage of air parcels in a PV cutoff experiencing decay whenever the PV cutoffs disappears on an individual isentrope (average annual number of events, 0% corresponds to pure reabsorption, 100% to complete diabatic decay), and (b,c) standard box plots (outliers not shown) of (b) mean PV and (c) area of the PV cutoff at the isentropic level from which it disappears for the histogram classes in (a).~~

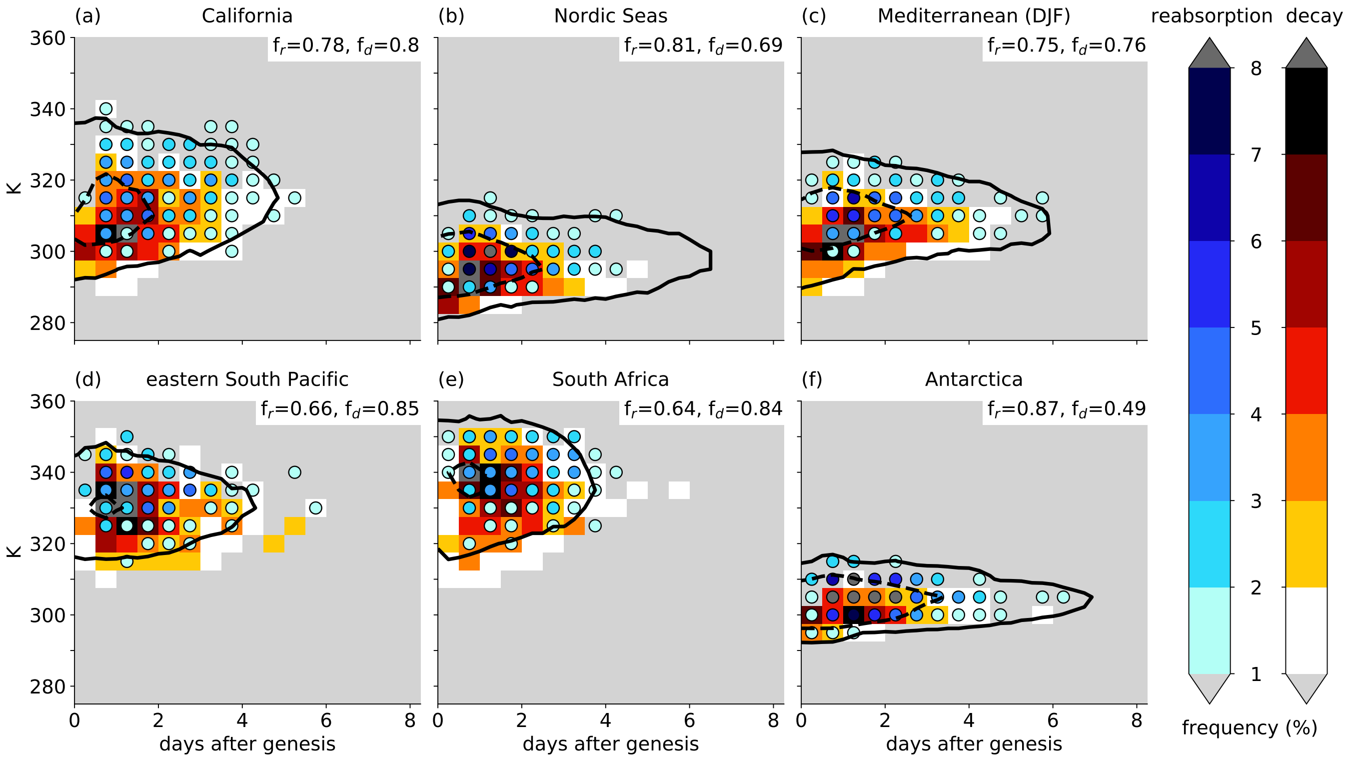

Figure 14. ~~Number~~ Relative frequency of reabsorption events (blue shaded circles, in %) and diabatic decay events (red shaded rectangles, in %) as a function of PV cutoff lifetime (binned into 12 hourly intervals) and isentropic level as well as the overall frequencies of at least one reabsorption event (f_r) or decay event (f_d) during the life cycle (numbers on top right of each panel). The climatological vertical evolution of the PV cutoffs is indicated by the black ~~contour (contour~~ contours for ~~55 PV~~ (solid) 30 and (dashed) 150 cutoffs as shown in Fig. **??**). Shown are the six genesis regions in DJF: (a) California, (b) ~~western North Atlantic~~Nordic Seas, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica.

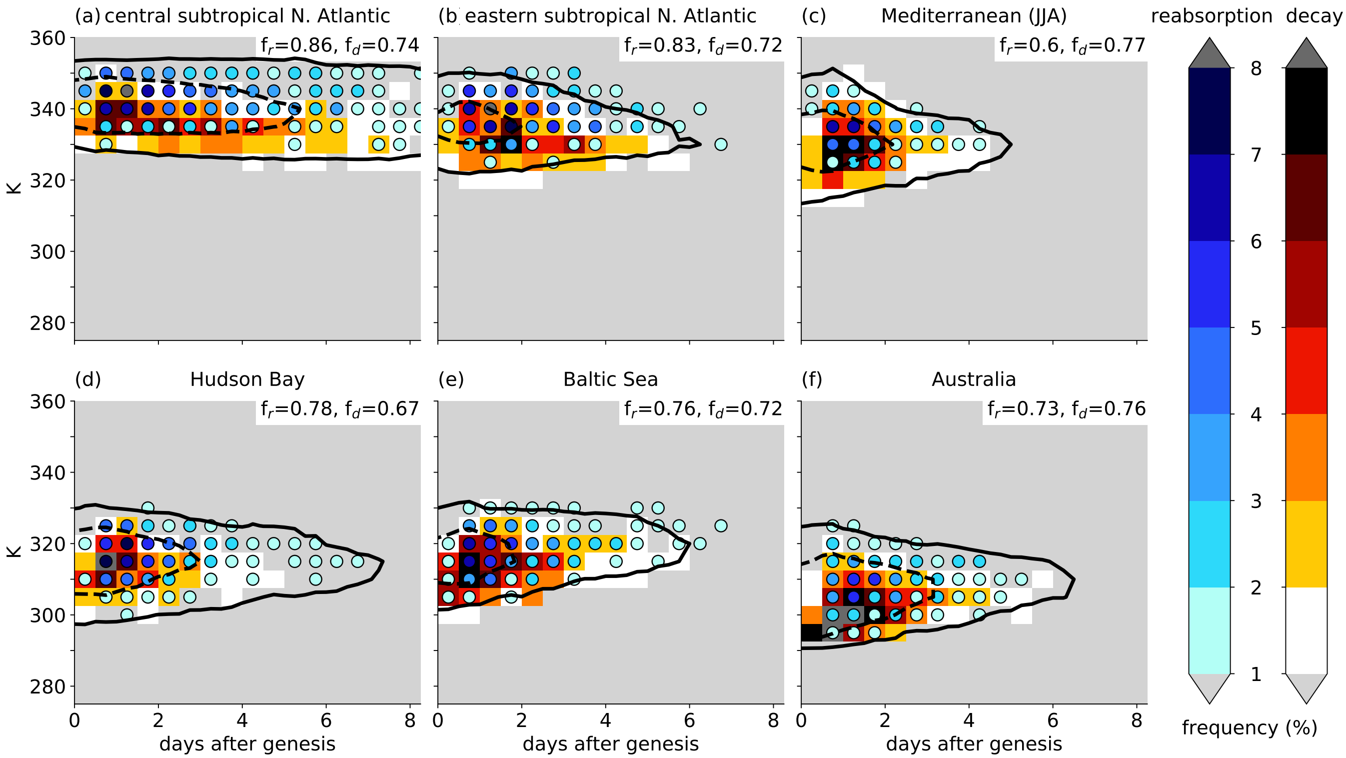

Figure 15. Same as Fig **??** but for JJA and (a) ~~Hudson Bay, (b)~~ central subtropical North Atlantic, (~~e~~b) eastern subtropical North Atlantic, (c) Mediterranean, (d) ~~Baltic Sea~~Hudson Bay, (e) Baltic Sea~~of Okhotsk~~, and (f) Australia.

~~Average number of (a,c) reabsorption (less than 50% decay, blue shading) and (b,d) diabatic decay (more than 50% decay, red shading) events per season within a distance of 500 km for (a,b) DJF and (c,d) JJA. As reference, the contour for two reabsorption events per season (blue contour) is shown in panels (b,d).~~

~~Median (solid lines) and lower and upper quartiles (dashed lines) of STT (red) and TST (blue) associated with PV cutoffs during the normalized life cycle (0: genesis, 1: lysis). The numbers in the normalized-time bins give the number of reabsorption and decay events, respectively. Shown are results for PV cutoffs in DJF from the genesis regions: (a) California, (b) western North Atlantic, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica.~~

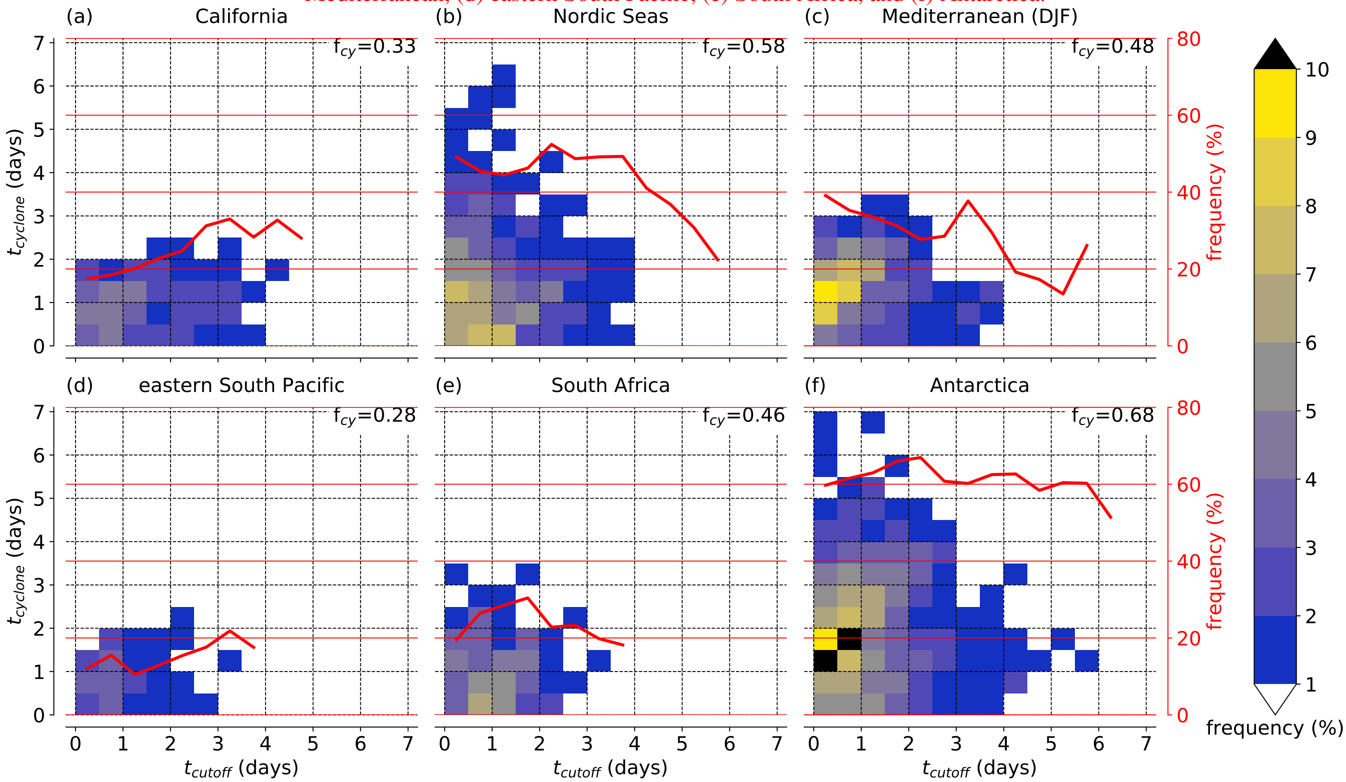

Figure 16. Relative frequencies of PV cutoffs linked to a surface cyclone (shading, in %) as a function of cutoff lifetimes (t_{cutoff}) on the horizontal axis and surface cyclone lifetimes ($t_{cyclone}$) on the vertical axis, binned into 12-hourly time intervals. The red contour shows the relative frequency of cutoffs linked to surface cyclones as a function of cutoff lifetime, e.g., the value at day 3 indicates the percentage of PV cutoffs with a lifetime of at least 3 days that are linked to a surface cyclone at day 3. PV cutoffs positioned in the lowermost row of the diagram are linked to a surface cyclone within 12 h after surface cyclogenesis and PV cutoffs positioned in the leftmost column of the diagram are linked to a surface cyclone within 12 h after PV cutoff genesis. The relative frequencies of PV cutoffs with at least one link to a surface cyclone during their life cycle are indicated at the top right in each panel (f_{cy}). Shown are results for PV cutoffs with genesis in DJF in the regions: (a) California, (b) Nordic Seas, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica.

~~Same as Fig **??** but for JJA and (a) Hudson Bay, (b) central subtropical North Atlantic, (c) eastern subtropical North Atlantic, (d) Baltic Sea, (e) Sea of Okhotsk, and (f) Australia.~~

~~Average net cross-tropopause mass flux associated with PV cutoffs (shading) and PV cutoff frequency (black contours, 1 and 5%) during (a) DJF and (b) JJA 1979-2017. Grid points with a PV cutoff frequency below 0.25% (approximately one per season) are not shown.~~

~~Total number of PV cutoffs linked to a surface cyclone (shading) as a function of cutoff lifetimes (t_{cutoff}) on the horizontal axis and surface cyclone lifetimes ($t_{cyclone}$) on the vertical axis (shading), binned into 12-hourly time intervals. The red contour shows the total number of cutoffs linked to surface cyclones as a function of cutoff life time. PV cutoffs positioned in the lowermost row of the diagram are linked to a surface cyclone within 12 h after surface cyclogenesis and PV cutoffs positioned in the leftmost column of the diagram are linked to a surface cyclone within 12 h after PV cutoff genesis. Total numbers of PV cutoffs with / without at least one link to a surface cyclone during their life cycle are indicated at the top right in each panel. Shown are results for PV cutoffs with genesis in DJF in the regions: (a) California, (b) western North Atlantic, (c) Mediterranean, (d) eastern South Pacific, (e) South Africa, and (f) Antarctica.~~

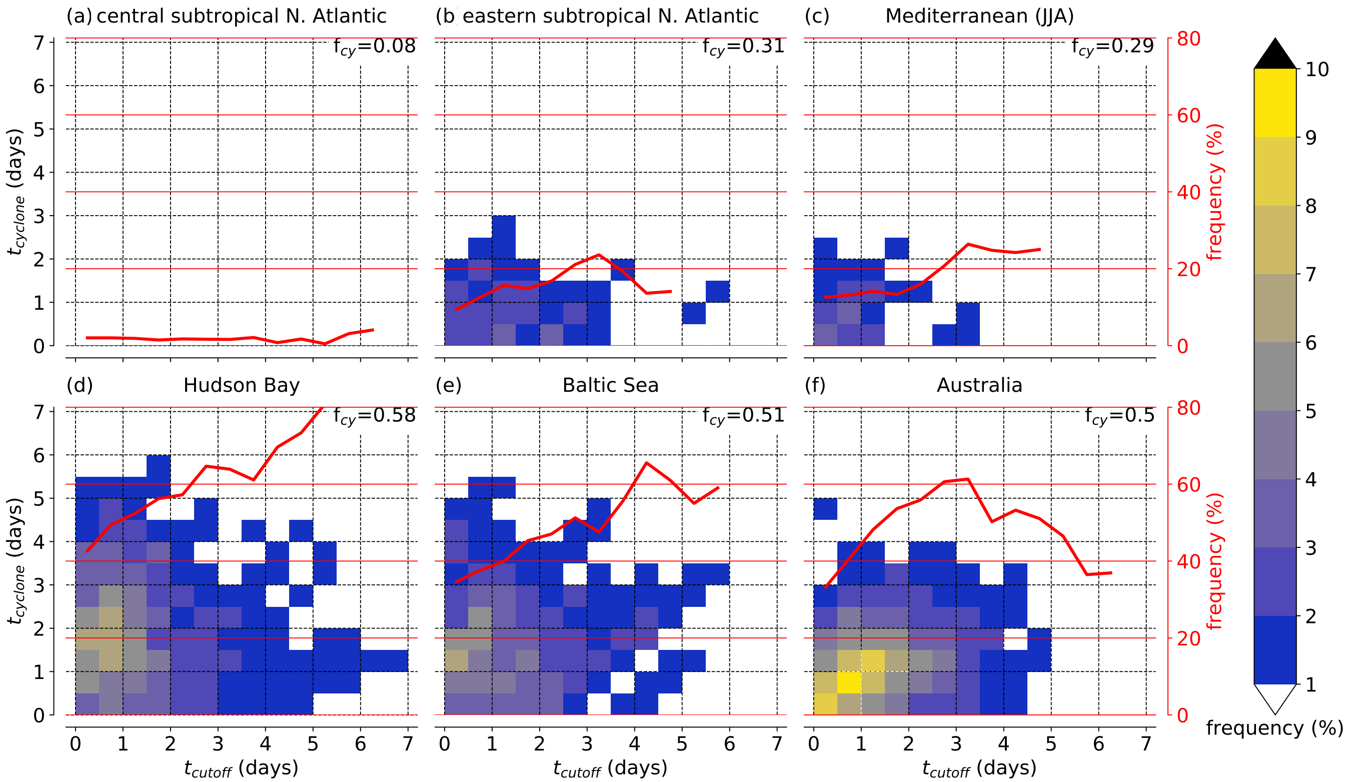

Figure 17. Same as Fig **??** but for PV cutoffs in JJA with genesis in the regions: (a) ~~Hudson Bay, (b)~~ central subtropical North Atlantic, (~~c~~b) eastern subtropical North Atlantic, (c) Mediterranean, (d) ~~Baltic Sea~~Hudson Bay, (e) Baltic Sea~~of Okhotsk~~, and (f) Australia.

~~Percentage of all PV cutoff tracks from 1979-2017 within four lifetime categories for the Northern Hemisphere (NH, 24933 tracks in total) and Southern Hemisphere (SH, 21420 tracks in total) 22% 33% 27 % 18% 21% 38% 28% 12% Same as Table **??** but for four categories of the distance between genesis and lysis. 15% 37% 21% 27% 9% 29% 24% 38%~~

Table 1. Characteristics of the three ~~proposed types of~~ PV cutoff ~~life cycles.~~ types

	Type I (*equatorward*)	Type II (*between-jets*)	Type III (*poleward*)
genesis regions	subtropical ocean basins	subtropics and mid-latitudes	storm tracks and high latitudes
prevailing genesis mechanism	strongly anticyclonic RWB	moderate anticyclonic RWB, can be followed by cyclonic break-up	cyclonic/neutral RWB
season	particularly summer	particularly winter	year around
average propagation speed	$1.3 \cdot 10E3\,\mathrm{km\,(day)^{-1}}$	$1.7 \cdot 10E3\,\mathrm{km\,(day)^{-1}}$	$2.0 \cdot 10E3\,\mathrm{km\,(day)^{-1}}$
range of isentropic levels	325 - 350 K	295 - 320 K	285 - 305 K
reabsorption/decay	decay particularly frequent	decay and reabsorption about equally frequent	reabsorption particularly frequent
intensitiy of associated precipitation	weakest	most intense	intermediate
frequency of link to surface cyclone	rare (7.7%)	intermediate (39.6%)	frequent (52.8%)