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A 15-YEAR CLIMATOLOGY OF STRATOSPHERE-TROPOSPHERE EXCHANGE AND ITS LINK TO POTENTIAL VORTICITY STREAMERS AND CUTOFFS

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1. INTRODUCTION

Trans-tropopause mass exchange gained a lot of interest in the last few years, not at least due to its chemical and climatological impact. Many approaches have been adopted in order to quantify the exchange rate and to identify the most prone regions for mass exchange. The review of Holton *et al.* (1995) primarily focused on the global aspects of cross-tropopause mass exchange. They calculated the zonally-mean mass flux by use of the residual mean diabatic circulation. On the other hand, mesoscale dynamical processes can be important for localized cross-tropopause exchange, for instance through the formation of stratospheric streamers, their breakup into cutoff lows, and diabatic decay (Appenzeller *et al.* (1996). Several case studies have been performed to study the exchange for such events.

In the present study, high-resolution data which cover the northern hemisphere are used to provide a 15-year climatology of cross-tropopause exchange *in the extratropics*. It builds upon the work of Bourqui (2001) and Wernli and Bourqui (2001) where a fully Lagrangian approach was adopted to identify (for a selected year) a distinct seasonal cycle and preferred regions for exchange. Furthermore, short-lived and long-lasting exchange events were discussed separately, since such a distinction is of major importance for the chemical impact of cross-tropopause exchange. Here, in addition to the study by Bourqui (2001), an objective analysis is performed in order to quantify the link between cross-tropopause exchange and near-tropopause streamers and cutoffs.

2. DATA SETS AND METHODOLOGY

The analyses in this study are based upon the 15-year ECMWF reanalysis, covering the years 1979-1993. The required fields are available every 6 hours on a latitude/longitude grid with 1° resolution and on 31 vertical levels from the surface up to 10 hPa.

2.1 Methodology for Exchange Climatology

A Lagrangian approach is used to obtain a climatology of cross-tropopause exchange (downward STE and upward TSE) on the extratropical northern hemisphere. Trajectories are started every 24 hours on a regular grid with a horizontal (vertical) grid spacing of 80 km (30 hPa) from 80 to 600 hPa on the entire hemisphere. “Preliminary exchange events” are selected for STE with the criterion that the trajectory’s PV value is above (below) 2 pvu at the beginning (end) of this 24 hour period (and vice versa for TSE). For every “preliminary exchange event” the trajectories are extended 4 more days both backward and forward in time. It is then verified that the air parcels reside for STE *at least* during a certain “threshold residence time” (for instance 48 hours) in the stratosphere *before* crossing the 2 pvu tropopause and for the same time period in the troposphere *after* the crossing (and vice versa for TSE). It is only these air parcels that are considered as “significant exchange events”, and parcels that move transiently to and fore across the interface on short time scales are eliminated. The analysis will be performed for threshold residence times of 24, 48, 72, and 96 hours.

2.2 Methodology for Streamer/Cutoff Climatology

The calculation of the streamer and cutoff climatology is separated into the following steps.

First, stratospheric and tropospheric streamers and cutoffs are identified on isentropic surfaces from 300 to 370 K, every 5 K. The identification relies on a contour searching algorithm, which tracks the 2 pvu contour on every of the isentropic surfaces on the northern hemisphere. Any isolated, closed 2 pvu contour is classified as a cutoff, and any “narrow”, “elongated” arc as a streamer. This procedure results in a classification of the air *on every isentropic level* as belonging to a stratospheric/tropospheric streamer or cutoff, or none of them. Fig. 1a shows an example with, for instance, a typical stratospheric streamer (sS) over the central Atlantic, smaller ones over the Asian continent next to an elongated tropospheric streamer (tS), and several small stratospheric and tropospheric cutoffs for instance over southern Spain (sC) and eastern Canada (tC). The relatively broad PV structure over central Europe is related to a synoptic-scale trough and is not classified as a streamer.

In a second step, the streamer and cutoff climatologies on the individual isentropic surfaces are “vertically integrated” over a subset of isentropic surfaces, which intersect the tropopause between 30°N and 60°N (solid thin lines in Fig. 1b). This procedure attributes to each latitude/longitude grid point a number of streamers and cutoffs that occur on any of the selected levels.

Note that a a simple summation over *all* isentropic levels would attribute too much importance to streamers and cutoffs which are not associated with mid-latitude tropopause dynamics, and would not account for the seasonal variations of potential temperature and PV. For summer, a subset with higher values of potential temperature has to be selected than for winter.

3. CROSS-TROPOPAUSE EXCHANGE

With respect to cross-tropopause transport, several aspects are of interest: Where does the exchange (downward STE and upward TSE) occur? What is the intra- and the inter-annual variability? And what is the vertical extent of the associated transport? In the following, these questions will be analyzed and briefly discussed.

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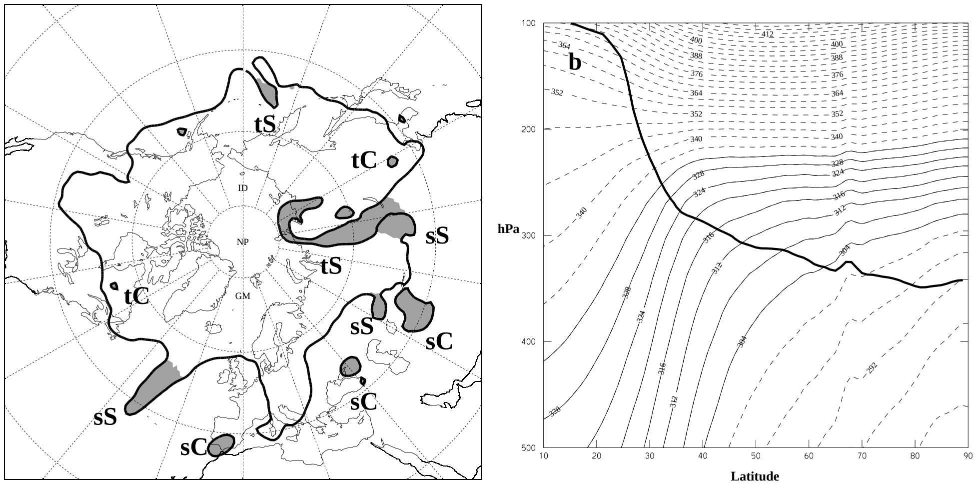

Figure 1: Illustration of the calculation of the streamer/cutoff climatology. (a) An example of objectively identified mesoscale features at 12 UTC 1 September 1980 on 330 K (shaded in grey). The labels refer to stratospheric streamers (sS), tropospheric streamers (tS), stratospheric cutoffs (sC) and tropospheric cutoffs (tC). (b) Potential temperature contours (light solid and dashed lines) and the 2 pvu PV isoline (bold), zonally and temporally averaged for February 1981. The solid isentropes are selected for vertical integration of the streamers and cutoffs on isentropic surfaces (see text).

3.1 Seasonal cycle and inter-annual variability

Time series which illustrate the variation of the monthly-mean net mass flux (STE-TSE) across the dynamical tropopause in the northern hemisphere ($0° - 90°$), are shown in Fig. 2. The four different curves correspond to the four threshold residence times (24, 48, 72 and 96 h). All curves show a distinct and robust seasonal cycle, with a maximum in winter and early spring and a minimum in summer and early autumn.

If a short threshold residence time (24 h) is applied, TSE dominates and the net mass flux is mainly negative. In contrast, for longer-lasting exchange events (48-96 h) the curves are fairly similar (which illustrates the convergence for increasing residence time) and the extratropical net mass flux is positive throughout the year [1]. If the curves for 48 h and 24 h are subtracted from one another, an approximately constant (negative) value results. This corresponds to the exchange events with a residence time *between 24 and 48 h* and illustrates that these short-lived events show only a weak seasonal cycle over the northern hemisphere and that TSE is more frequent than STE. Note also that a vanishing *net* cross-tropopause flux implies cancellation of STE and TSE fluxes and not necessarily that they are zero on their own (not shown). This is of importance if the chemical impact of cross-tropopause flux is considered. With respect to the chemical impact, the most interesting exchange events are those that reach near-surface heights and allow mixing of stratospheric with boundary-layer air. In the present study, a deep STE event is defined to reach regions below 700 hPa, and a deep TSE event to originate from below 700 hPa. Time series for the horizontally integrated frequency of deep STE and TSE (with a threshold residence time of 48 h) are shown in Fig. 3a. The distinct and robust seasonal cycle of deep STE, and to a lower degree the one of deep TSE, is evident. Again, maxima are observed in winter and early spring, whereas nearly no deep events occur in summer and early autumn. Although both, the overall cross-tropopause flux and the one associated only with deep events, show a robust seasonal cycle, significant year-to-year variations exits. If all exchange events are considered (Fig. 2), significantly more events occurred for instance in the (El Nino) year 1987 than in the previous year 1986. This still holds if only deep exchange events are considered. Note also the relatively large spread in the frequency of deep STE during winter months which is illustrated in Fig. 3b. It is of major interest to attribute this observed year-to-year variability to distinct dynamical structures (e.g. cyclones, streamers and cutoffs) and atmospheric climatological patterns (like the North Atlantic oscillation or the El Nino southern oscillation). Finally, note that the curves in Fig. 2 and 3 show no significant trend, both for all and for deep exchange events only.

[1] Note that this annual mean net downward mass flux is compensated by upwelling in the tropical regions, and that this part of the global circulation is not captured by the present analysis (on the one hand because the vertical motions associated with deep tropical convection are not accurately represented by ECMWF analyses, and on the other hand because the use of northern hemispheric data only does not allow the calculation of trajectories near the equator over several days.

3.2 Geographical distribution

In the previous subsection, only the hemispherically integrated exchange was considered. Here, it is shown that in addition to the robust seasonal cycle, a robust geographical distribution of exchange events can be identified. Figure 4 shows some selected results for the winter season which illustrate the geographical distribution of STE and TSE. The net (STE-TSE) cross-tropopause mass flux (Fig. 4a) shows that the mid-latitudes (especially the North Atlantic and Pacific storm track regions) are predominantly associated with STE, whereas in the (sub-)tropics and the Arctic region TSE dominates (note again that the present analysis does not account for TSE associated with the tropical upwelling). An interesting feature is the extended region of net upward exchange over northern Canada and Greenland, a region where the tropopause is typically very low. If only deep STE events are considered (Fig. 4b), the regions of maximum ex-

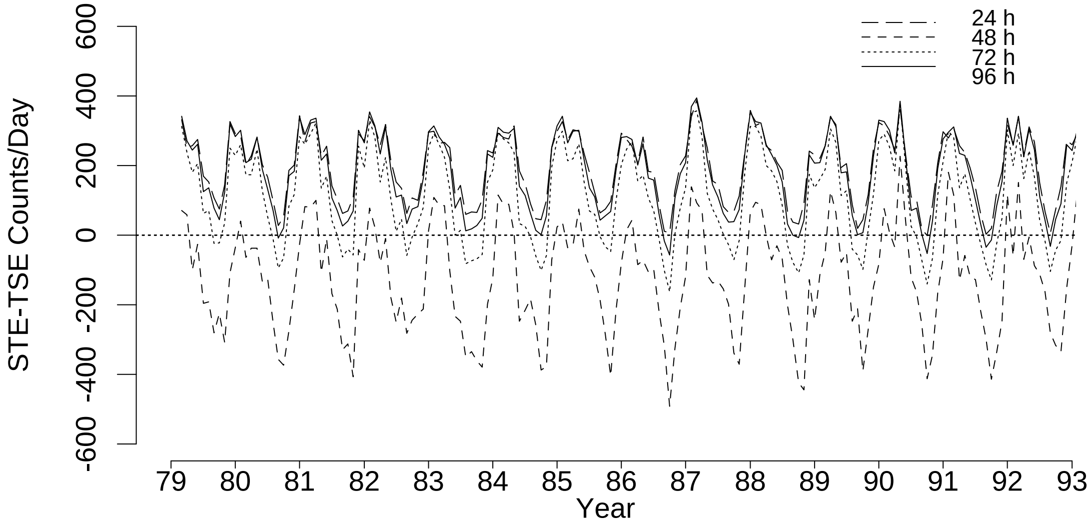

Figure 2: Time series of the net (STE-TSE) mass flux across the 2 pvu tropopause in the northern hemisphere (0-90°N). The horizontal axis denotes the year, the vertical axis the net number of exchange events (every event corresponds to $20 \cdot 10^{11}$ kg). The four line styles correspond to the four threshold residence times 24, 48, 72 and 96 h (see text for details).

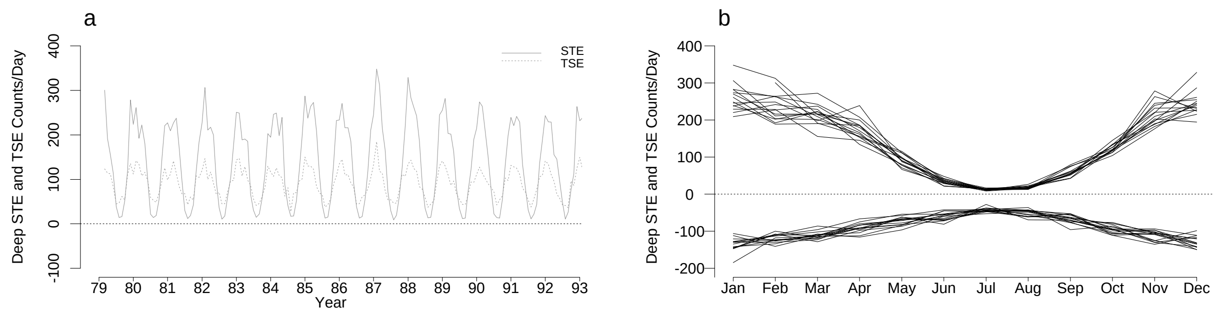

Figure 3: Deep STE and TSE events (selected with a threshold residence time of 48 h). (a) Time series of the associated mass flux across the 2 pvu tropopause. The horizontal axis denotes the year, the vertical axis the number of deep STE (solid) and deep TSE (dotted) exchange events in the northern hemisphere (every event corresponds to $20 \cdot 10^{11}$ kg). (b) The seasonal cycle for every individual year from 1979-1993. Positive values are for deep STE, negative ones for deep TSE.

change are also restricted to the storm tracks and weaker secondary maxima occur over the Alps and north of the Himalayan mountains. Deep TSE is scarcely found in the subtropics, its maximum is over the western Atlantic and the southern tip of Greenland (not shown).

Figures 4c,d show the regions below 700 hPa which are "connected" to the stratosphere, either by deep STE or TSE. Whereas in the Pacific region the low-tropospheric areas which are intruded by stratospheric air lie predominantly at the end of the storm track (Fig. 4c), a more complex picture exists for the Atlantic region. Here, many deep STE events occur at the beginning of the storm track, over the North American continent. With respect to deep TSE events, the North Atlantic and the North Pacific show a similar qualitative behavior (Fig. 4d). The near-surface regions from where deep TSE events transport near-surface air into the stratosphere, correspond to the beginning of the storm tracks over the western Pacific and Atlantic oceans near 35°N. This transport is associated with moist ascending airstreams within cyclone systems (Wernli 1997; Stohl 2001).

For the other seasons (spring to autumn) the amplitudes are weaker in accordance with the results of section 3.1. In addition, some changes in the geographical distribution occur. For instance, while during winter the net exchange has a more or less uniform amplitude over the Pacific ocean (Fig. 4a), it is more localized over the western United States during spring (not shown). With respect to deep STE, during winter a distinct maximum occurs at the beginning of the Pacific storm track, whereas no such maximum is discernible in the other seasons. In accordance with the diminished tendency for deep STE in summer (see Fig. 3), significantly less regions below 700 hPa are "connected" by rapid vertical transport to the stratosphere in summer than in winter. Furthermore, the winter maximum over the eastern United States (see Fig. 4c) vanishes in the other seasons. The low-tropospheric regions which are connected to the stratosphere by deep TSE remain situated at the beginning of the Pacific and Atlantic storm tracks (as in Fig. 4d) for winter, spring, and autumn.

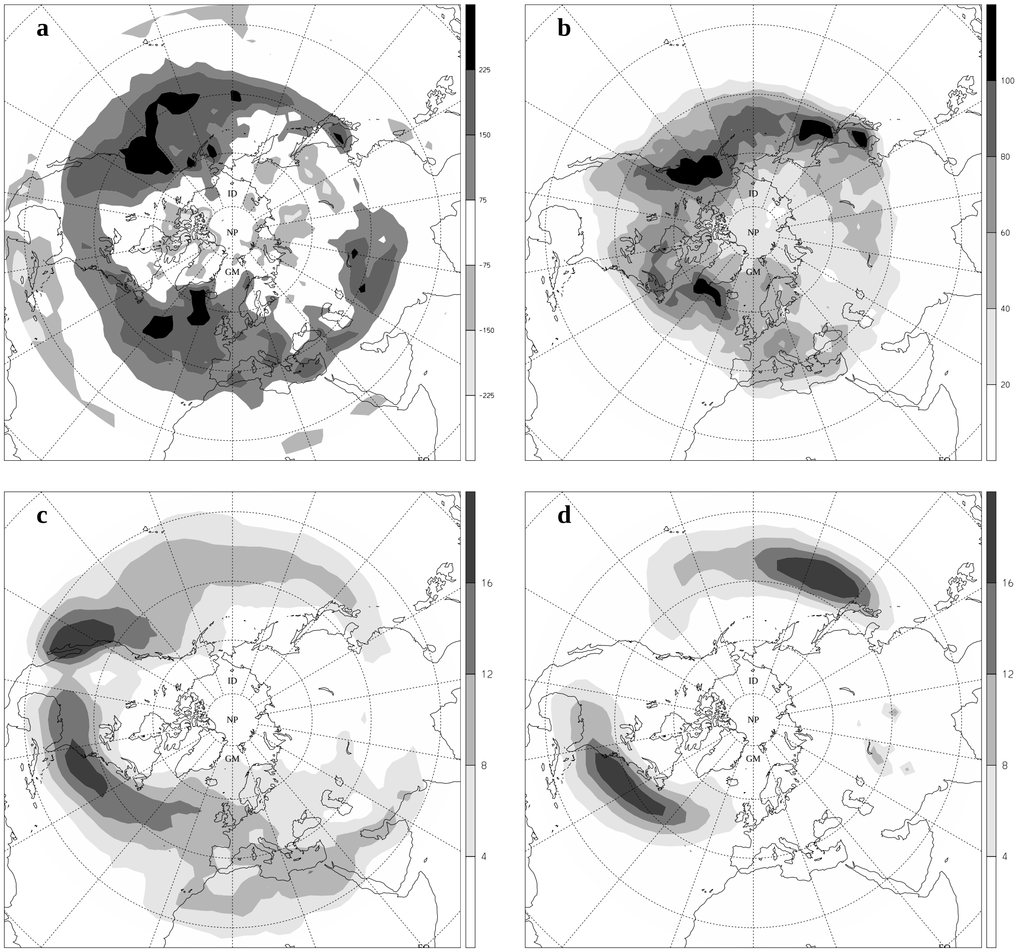

Figure 4: Selected results for the 15-years winter mean geographical distribution of STE and TSE. (a) The net (STE-TSE) cross-tropopause mass flux, (b) deep STE events only, (c) points below 700 hPa which are connected to the stratosphere by a deep STE event, and (d) points below 700 hPa which are connected to the stratosphere by a deep TSE event. For all figures a threshold residence time of 48 h has been used and the domain north of 15°N is plotted.

4. STREAMERS AND CUTOFFS

Stratospheric streamers and cutoffs are related to intrusions of stratospheric air into the troposphere, and vice versa for tropospheric streamers and cutoffs. In Fig. 5 a decomposition of monthly mean time-series for (a) tropospheric cutoffs, (b) tropospheric streamers, (c) stratospheric cutoffs, and (d) stratospheric streamers is presented. Every panel contains four time-series, which are from top to bottom: the original time-series with monthly mean values, a trend estimate, a seasonal cycle, and a remainder. The original time-series is the sum of the lower three time-series. Note that the scales for the four time series are different. Streamers and cutoffs (stratospheric and tropospheric) show only a very weak trend, but a distinct and quite robust seasonal cycle. A pronounced maximum for stratospheric cutoffs occurs in summer, flatter maxima for stratospheric streamers and tropospheric streamers and cutoffs in late summer to early winter. Minima are observed in late spring for all four processes. Finally, the amplitude of the remainder in the decomposition is comparable to the one of the seasonal cycle. This emphasizes the importance of distinct events which cannot be attributed to quasi-periodic seasonal variations.

5. LINK BETWEEN EXCHANGE AND STREAMERS/CUTOFFS

Since streamers and cutoffs are associated with baroclinic wave breaking, i.e. with strong dynamical activity near the tropopause, they are expected to be associated with cross-tropopause mass exchange. Two strategies were adopted in order to quantify this relationship.

Table 1 summarizes the results for the first strategy. It is checked for every STE, TSE, deep STE (dSTE in the table), and deep TSE (dTSE) event in January 1980 whether a point belonging to a stratospheric or tropospheric streamer (sS, tS) or cutoff (sC, tC) can be found in its neighborhood (300 km in the horizontal and 5 K in the vertical). Furthermore, such a point must be within plus/minus 1 h of the exchange event itself. Remarkably large percentages are found. For instance, about 77%

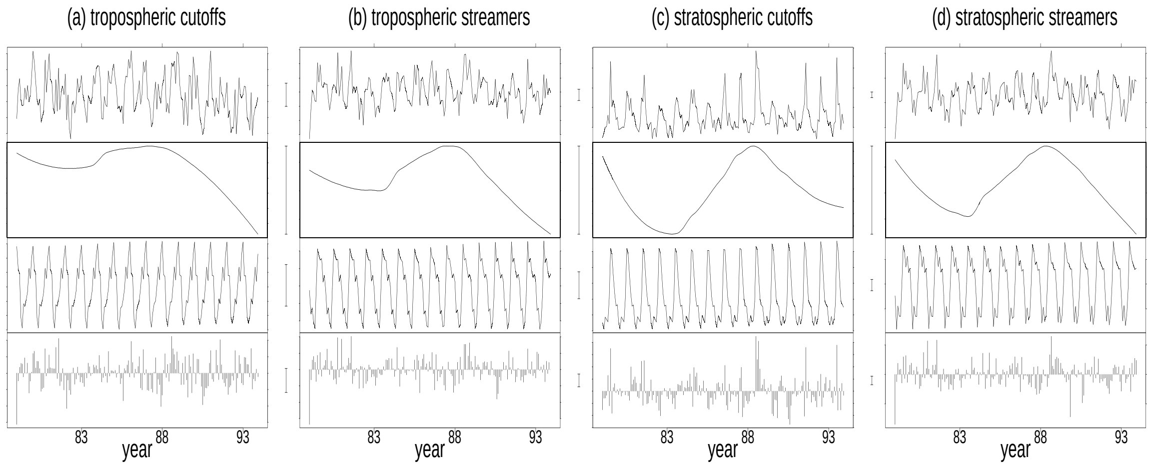

Figure 5: Decomposition of the time-series for (a) trop. cutoffs, (b) trop. streamers, (c) strat. cutoffs and (d) strat. streamers. In every panel, the uppermost curve gives the original time-series, which is the sum of the lower three curves which are (from top to bottom) trend, seasonal cycle and remainder. Note that the scales for the different curves are different (the relative scale is indicated by the vertical bars to the right of the diagrams).

of deep STE events occur in the vicinity of stratospheric cutoffs.

	tC	tS	sC	sS
STE	21	22	49	40
TSE	36	28	35	34
dSTE	7	9	77	33
dTSE	27	28	50	38

Table 1

A slightly different question is answered by Table 2, where it is checked for every streamer and cutoff in January 1980, whether an exchange event (STE, TSE, dSTE, dTSE) can be found in the neighborhood (300 km in horizontal and 5 K in vertical) of the streamer or cutoff. Again, a time window of plus/minus 1 h was applied. Note that now about 4% of stratospheric cutoffs are associated with deep STE. Hence, most deep STE event are linked to stratospheric cutoffs (Table 1), but only few stratospheric cutoffs are linked to deep STE events (Table 2). Finally, if shallow exchange events are also considered, the percentages are comparable to those in Table 1. This confirms the important role of streamers and cutoffs for cross-tropopause exchange.

	STE	TSE	dSTE	dTSE
tC	18	32	1	5
tS	53	69	6	14
sC	37	25	4	3
sS	66	58	10	11

Table 2

Repeating the calculations for September 1980 yields similar numbers except for the deep exchange values in Table 2 which are about an order of magnitude smaller than for January. This indicates for instance that deep STE events in September are still likely to be associated with a stratospheric cutoff; but a stratospheric cutoff in September is rather unlikely to be related to a deep STE event. This is in accordance with Figs. 3 and 5c, which show that during autumn many stratospheric cutoffs occur but nearly no deep STE.

6. DISCUSSION

The first 15-year climatology of cross-tropopause mass exchange over the northern hemisphere was presented, together with a corresponding climatology of stratospheric and tropospheric streamers and cutoffs. With respect to the exchange climatology the capability and usefulness of the Lagrangian approach was demonstrated.

Furthermore, the two separate climatologies were cross-analyzed in order to quantify the link between streamers and cutoffs on the one side, and cross-tropopause mass flux on the other side. It was shown that a remarkably strong link between the two exists. This highlights the importance of baroclinic wave breaking for the exchange climatology of mass and chemical constituents across the extratropical tropopause.

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REFERENCES

Appenzeller, C., H. C. Davies and W. A. Norton, 1996. Fragmentation of stratospheric intrusions. *J. of Gephys. Res.* **101,** 1435-1456.

Bourqui, M., 2001. Analysis and quantification of STE: A novel approach. PhD thesis, Swiss Federal Institute of Technology

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood and L. Pfister, 1995. Stratosphere-troposphere exchange. *Rev. of Geophys.* **33,** 403-439.

Stohl, A., 2001. A one-year Lagrangian “climatology” of airstreams in the northern hemisphere troposphere and lowermost stratosphere. *J. of Gephys. Res.*, in press

Wernli, H., 1997. A Lagrangian-based analysis of extratropical cyclones. II: A detailed case study. *Quart. J.Roy. Met. Soc.* **123,** 1677-1706.

Wernli, H. and M. Bourqui, 2001. A one-year Lagrangian “climatology” of (deep) cross-tropopause exchange in the extratropical northern hemisphere. Submitted to *J. of Gephys. Res.*