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EPISODES OF ALPINE HEAVY PRECIPITATION WITH AN OVERLYING ELONGATED STRATOSPHERIC INTRUSION: A CLIMATOLOGY

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ABSTRACT

This study discusses the role of stratospheric intrusions (determined as potential vorticity (PV) streamers) as upper-level instigators of heavy precipitation along the Swiss Alpine south side (AS) on a climatological timescale. A climatology of streamers is used compiled on the basis of the ECMWF 40-year re-analysis data set (ERA-40). Days of extreme and heavy precipitation along the Swiss AS are determined from an existing observational Alpine precipitation climatology. For these days, the presence of streamers over western Europe as well as their location and orientation is recorded. On 73% of the extreme precipitation days, a streamer is situated over western Europe. The mean spatial frequency distribution of the streamers on the extreme precipitation days exhibits a structure that resembles in its form and location the 'archetypal heavy precipitation streamer' known from case studies. The frequency maximum is situated over southern England and the west coast of France. The same analysis is applied to three sub-domains (Valais, Grisons, Ticino) along the Swiss AS. Significant differences in the location and the orientation of the streamers for the sub-domains are found. The majority of streamers associated with heavy rain in the western-most sub-domain (Valais) are oriented in a cyclonically-sheared fashion, while for the Ticino the streamers are more anti-cyclonically orientated.

Differences for events of increasing severity are analysed by comparing the form, location, amplitude (PV), and persistence of the streamers on extreme and heavy precipitation days. The precipitation distribution is shifted to higher intensities for more persistent streamers. There is no detectable difference found in the form parameters, but the southerly moisture flux into the domain is significantly larger during extreme precipitation days than during heavy precipitation days. Likewise, the seasonal variation in the percentage of streamer-related heavy precipitation, which is highest in autumn (85%), can be related to the seasonal variation of southerly moisture fluxes. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: heavy precipitation; PV-streamer; precursor; extreme events; moisture flux; wave-breaking

1. INTRODUCTION

The Alps are not only the water tower of Europe, receiving markedly more annual precipitation than the neighbouring regions, but also some Alpine sub-domains experience a much higher frequency of heavy precipitation (HP) events than other locations in central Europe (Frei and Schär, 1998). The frequency maxima are located predominantly on or in close proximity to the Alpine south side (AS).

Sustained precipitation in a sub-domain is favoured by an ambient environment that is conditionally unstable; a forcing that anchors the system to the vicinity, and an adequate flux of moisture towards the system. These conditions are met on the AS when a moist low-level air mass is advected toward the Alpine ridge so that the forced upslope ascent constitutes a trigger for the precipitation system, and likewise the terrain can help anchor the system. Detailed case-study analyses and numerical model simulations of HP events in this region have been conducted within the framework of the Mesoscale Alpine Programme (MAP) to examine the *in situ* dynamics and forcing (e.g. Buzzi *et al.*, 1998; Houze *et al.*, 2001). The mesoscale structure of the

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system and the precise location of the precipitation maxima will be sensitive to the mesoscale dynamics and the finer-scale features of the terrain, whereas the structure and intensity of the incident airstream is, to a large measure, established by the large-scale flow pattern. It is the nature, role, and significance of the latter pattern that forms the theme of the present study.

Some previous studies have considered aspects of the linkage between HP events in specific regions of the Mediterranean and the structure of the ambient mid- and upper-tropospheric flow. For example, HP events over Spain and the central Mediterranean have been linked with upper-level troughs extending southward towards the HP region (Jacobeit, 1987; Romero *et al*., 1999). However, an attempt to link HP events in several Alpine sub-domains with large-scale weather regimes, as identified by a cluster analysis of the 700 and 500 hPa field, produced ambivalent results (Plaut and Simonnet, 2001; Simonnet and Plaut, 2001). The inference drawn was that the HP events in these sub-domains were probably associated with rarely occurring circulation patterns. Again, studies of HP events in Tuscany, along the Ligurian Coast and on the Piedmont indicate that, despite their spatial proximity, distinctively differing flow patterns prevail for the three regions (Rudari *et al*., 2005).

In the present study, attention is centred on episodes of heavy Alpine precipitation that are accompanied by the presence of meridionally-elongated stratospheric intrusions over western Europe. The intrusions signify streamers of high potential vorticity (PV) extending equatorward from the reservoir of high PV in the polar lower stratosphere (Appenzeller and Davies, 1992). Streamers whose equatorward portion form a cut-off over the Mediterranean have been linked to the occurrence of Alpine lee-cyclogenesis (e.g. Lanzinger, 1992), whereas quasi-stationary elongated streamers have been identified as precursors of Alpine HP events (Massacand *et al*., 1998; Fehlmann *et al*., 2000). The basis for the latter linkage is that a meridionally-elongated streamer is accompanied by a distinctive flow and thermal structure comprising an ascending southerly flow component on their eastward flank and reduced static stability beneath the streamer, so that their arrival over southwestern Europe is conducive to the triggering and maintenance of Alpine HP events. In particular, a quasi-stationary streamer located west of the Alps can contribute significantly to the strength of the flow incident upon the Alpine ridge throughout its sojourn in the region. It is these considerations that prompted the study of upper-level streamers to form one of the MAP foci (Bougeault *et al*., 2001).

It was noted earlier that the amplitude and localization of the precipitation is influenced by the moisture content of the low-level air and by the nature of the airflow in the immediate vicinity of the Alps (Gheusi and Davies, 2004), and the presence of a streamer has a bearing upon both these effects. For the moisture content, the Atlantic and the Mediterranean are potential sources (Reale *et al*., 2001; Koch, 2004; Turato *et al*., 2004), and the streamer's quasi-stationarity can influence the accumulation of moisture by the incident airstream. This is evident in the Lagrangian trajectories of incident air parcels (see e.g. Massacand *et al*., 1998; Koch, 2004). Likewise, the nature of the near-Alpine flow depends upon the strength, direction, and stability of the incident flow, and again a streamer can modify these factors. Indeed, it has been shown that the streamer's internal structure can radically change the location of the precipitation maximum (Fehlmann *et al*., 2000).

In the present study, we examine the link between streamers and HP from a climatological standpoint, and address the following questions:

(1) How robust and significant is the link between the upper-level PV-structures and Alpine HP events?
(2) How is the probability of extreme precipitation over the AS modified by the presence of an upper-level disturbance?
(3) What is the effect of the streamer's persistence upon the precipitation?
(4) Does the position and form of the intrusion relate to the local distribution of the precipitation?
(5) How do additional factors such as the moisture advection influence the precipitation distribution?

A description of the data set and the methodology is provided in Section 2. In Section 3, a diagnosis is made of the frequency and nature of streamers during HP events. Consideration is given to their preferred location and orientation both on the AS and for three specified sub-regions. In Section 4, the obverse aspect is examined by studying the dependency of the precipitation upon the presence of a streamer. The seasonal variability of the coupling between streamers and precipitation and trends are discussed in Section 5. Differences in the shape and intensity of streamers for heavy and extreme precipitation are addressed in Section 6. Conclusions follow in Section 7.

2. DATA AND ANALYSIS PROCEDURES

2.1. The basic ingredients

Two major climatological data sets are derived and analysed in the present study. The first is extracted from the daily high-resolution precipitation data set for the entire Alpine region compiled by Frei and Schär (1998) for the period 1966–1999. It covers the Alpine region and adjacent areas with a horizontal resolution of approximately 25 km and is obtained from rain-gauge measurements from more than 6600 stations. From this source data set, a climatology is derived from the area-mean precipitation for the AS and three sub-regions–the Ticino (TI), the Grisons (GR) and the Valais (VS), and precipitation events are analysed separately for each region. The AS region provides an aggregate precipitation for the south side, while the other regions correspond to three distinct watersheds. The TI region is located south of the main ridge and has the highest frequency of HP events of the entire Alpine region (Frei and Schär, 1998), whereas the GR and VS regions correspond to inner-Alpine roughly east–west aligned catchments. The four domains are demarked in Figure 1 along with displays of the topography of the Alpine ridge itself and an indicator (see following text) of the frequency of HP events in the AS region. Note that the scale of the domains are such that the AS region comprises 48 grid-points in the database and the three other regions 12 grid-points.

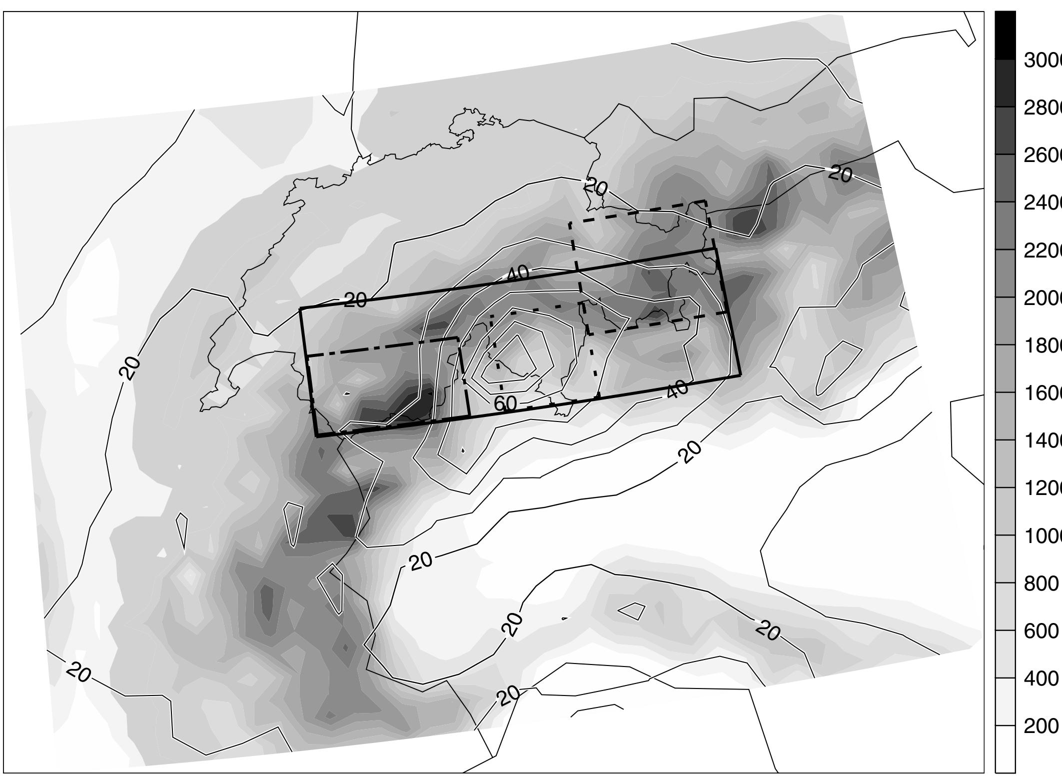

Figure 1. Topography of the Alps (shaded, from Frei and Schär (1998), resolution ∼25 km), precipitation distribution for the AS-EX1P days (mm/day) (black isolines) and the different investigation areas: (1) the whole Swiss Alpine south side (AS) (45.9°–46.7 °N, 6.9°–10.5 °E) (solid box); (2) the Ticino (TI) (45.8°–46.5 °N, 8.5°–9.3 °E) (dotted box); (3) the Grisons (GR) (46.3°–47 °N, 9.3°–10.5 °E) (dashed box); and (4) the Valais (VS) (45.6°–46.4 °N, 6.9°–8.2 °E) (dash-dotted box)

HP events are grouped into three categories representing respectively the highest 124, the 621, and the 1242 days of area-averaged precipitation, corresponding to the 1%, 5%, and 10% precipitation quantile of all days. Hereafter, these are referred to as the EX1P, EX5P, and EX10P categories, and they correspond respectively to the occurrence of an AS-area-mean precipitation of more than 29.1, 16.1, and 10.6 mm/d. In the following sections, results will be presented primarily for the extreme EX1P category, but reference will also be made to the less severe categories. The mean precipitation distribution during the AS-EX1P days is displayed in Figure 1. The precipitation maximum lies in the region of the TI, the rain amount for the VS region is less, whereas the GR is intermediate. This HP distribution is similar to the mean climatological Alpine precipitation distribution that is also characterized by a maximum in the TI with dryer conditions in the VS and the GR (Figure 9 of Frei and Schär (1998)). Seasons are defined here as the respective 3-monthly periods for winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

The second major data source is the ERA-40 global re-analysis data set of the ECMWF. It is available for the 1957–2002 period at 6-hourly intervals, and a horizontal resolution corresponding to a spherical truncation of T159 with 60 vertical levels (Simmons and Gibson, 2000). This data set is used to extract a streamer climatology following the method introduced by Wernli and Sprenger (2005). First the 6-hourly ERA-40 fields are interpolated onto a 1×1 degree grid. Then the hydrostatic form of the Ertel-PV field is calculated and interpolated on nine pre-selected potential temperature levels (i.e. from 310–350 K at 5 K intervals). These are the surfaces that approach or intersect the tropopause in the mid-latitudes (*cf* climatological cross-section in Figure 1 in Liniger and Davies, 2004)). On each level, the PV = 2 contour is adopted as the dynamical tropopause separating stratospheric (PV > 2 pvu) from tropospheric air, and then streamers are identified as narrow (<800 km) filaments of stratospheric air. For more details on the technique, the reader is referred to Wernli and Sprenger (2005). Utilising this climatology, a catalogue of the spatial distribution of streamer occurrence is established by constructing composite two-dimensional fields formed by assigning a value 1 within a streamer, and value 0 elsewhere. Moreover, the following additional parameters are calculated to further characterize the structure of the streamer: (1) orientation, (2) maximum amplitude and (3) lifetime. Parameter (1) is derived subjectively directly from the PV = 2 contour. Parameter (2) is taken as the upper 90% quantile of the isentropic PV values within each streamer. Parameter (3) is determined simply as the streamer persistence within a pre-specified domain.

The ERA-40 set is also used to estimate the larger-scale horizontal moisture flux vector ($\mathbf{q} \times \mathbf{v}$), and thence the component perpendicular to the boundaries of the AS box. In practice, the 6-hourly net fluxes of specific humidity were calculated by integrating vertically from the surface (i.e. lowest model level) to 150 hPa and then normalizing the result to yield the total water mass per unit surface area [kg/m^2] across each boundary of the AS box. The sensitivity towards the upper boundary has been investigated, and the higher levels have been found to contribute merely negligible amounts of moisture to the entire column.

2.2. *Approach*

A twofold strategy is adopted to examine the climatological link between HP events and upper-level streamers. The first component is to establish a climatology of streamer and precipitation characteristics during the co-occurrence of HP events and streamers. The second component involves examining the influence of a streamer's presence upon the precipitation, as a function of the latter's intensity. For both components, two additional criteria are imposed on the streamers. The first arises from the different temporal resolution of the precipitation and streamer data sets. The occurrence of streamers is logged every 6 h and at each time step their existence is noted on seven isentropic levels (310 K–340 K). For temporal compatibility, the largest streamer is selected on the basis of the maximum streamer area on an isentropic surface in the 24-h period. In the majority of cases, the largest streamer also extends furthest equatorward and downward, and hence this choice tends to capture the dynamically most significant streamers. The second criterion is a spatial selection introduced to exclude streamers that are situated too far eastward to influence southern Alpine precipitation. Streamers are excluded from the climatology if they do not overlap with a rectangular region centred over western Europe (43°–50 °N, 5 °W–10 °E) (see the box in Figure 2(a)). Comparison of streamer composites extracted from the climatology on HP days with or without the application of this second criterion exhibit

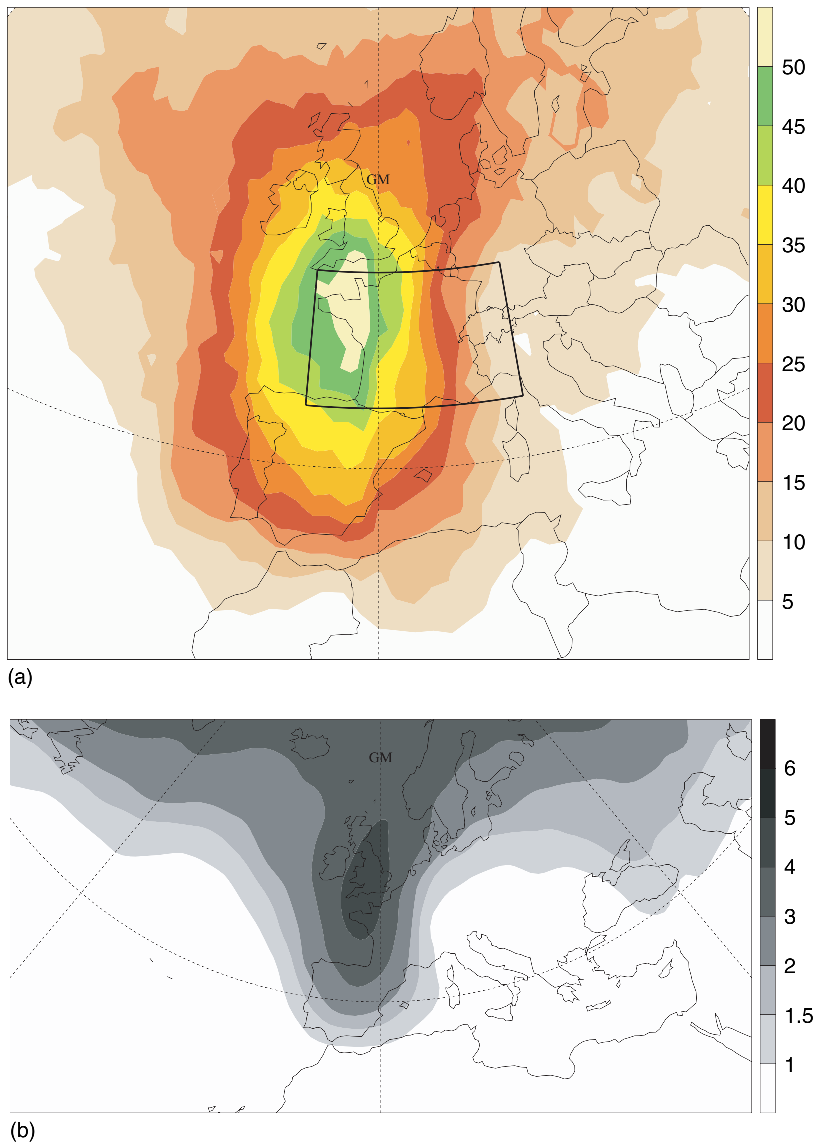

Figure 2. (a) Frequency distribution of the streamers (%) during the 124 AS-EX1P days (shaded). The box used for the streamer selection. See text for details. (b) Mean isentropic PV on AS-EX1P days with streamers (pvu)

the same overall structure. This is in line with the earlier result that troughs situated in approximately the box exert the largest influence on the precipitation in the longitudinal range of the Swiss Alps (Jacobeit, 1987).

3. STREAMERS ON HEAVY PRECIPITATION DAYS

In this section, consideration is given to upper-level streamers present during HP days in the EX1P category. Their statistically preferred distribution and orientation is examined for both the AS and the individual sub-domains.

3.1. Composites of streamer frequency

3.1.1. Alpine south side. The joint analysis of precipitation and streamers shows that on 73% of the HP days on the Alpine south side (i.e. 91 out of 124 days) an upper-level streamer was present over western central Europe. We will return to discuss the nature of the non-streamer HP events later in Section 5.1.

An indication of the HP-streamers' spatial location is obtained by constructing a frequency composite displaying their occurrence at each grid-point (Figure 2(a)). The composite for these EX1P days on the Alpine south side (AS) exhibits a coherent meridionally-aligned spatial structure extending from Scotland to the south of Spain. This pattern bears comparison, both in form and location, with that of streamers that accompanied several major HP events in the Alpine region (Massacand *et al*., 1998). Recall that a frequency maximum greater than 50% denotes the presence of a streamer at these grid-points on more than half of these EX1P days. The concomitant tropospheric flow features a strong and vertically coherent southerly component towards the Alpine mountain chain (not shown). The corresponding composites for the two other larger number and weaker in intensity categories (the AS-EX5P and AS-EX10P days) are qualitatively similar (not shown). For 71% of the AS-EX5P (446 out of 621 days) and 69% of the AS-EX10P (862 out of 1242 days), an upper-level streamer was present. In short, the frequency maxima decrease with increasing sample size (42 and 38% for the respective composites) and the composites' spatial structures become slightly less confined.

The above frequency-based distribution can be compared with a physically-based composite of the corresponding mean PV field on the isentropic surface selected on the basis of the largest-streamer-criterion outlined above (Figure 2(b)). Again the composite of the 91 cases shows a distinct PV-anomaly over Europe in the form of an elongated streamer with a mean PV maximum between 4 and 5 pvu that is co-located with the frequency-based pattern.

The frequency distribution for the counter composite comprising all streamers on non-AS-EX10P days is centred further southeast over northern Italy, and it has a lower amplitude and a much more diffuse shape (Figure 3). Several points are pertinent to the interpretation of this figure. First, the shift in location is consistent with streamers located over or south of the Alps and thereby less conducive to producing HP on the immediate Alpine south side. Second, the amplitude and shape changes are partly attributable to the larger number of days captured in this sample, but the changes are also consistent with a reduction in the streamers' 'precipitation efficiency', i.e. the capability of a streamer to induce a certain amount of precipitation, which can depend on factors such as the streamer-related flow amplitude and direction, the vertical stability, or the availability of moisture. Finally, note that the occurrence of small-to-moderate amounts of precipitation might also be associated with the rapid eastward propagation of a streamer across the Alpine region, or

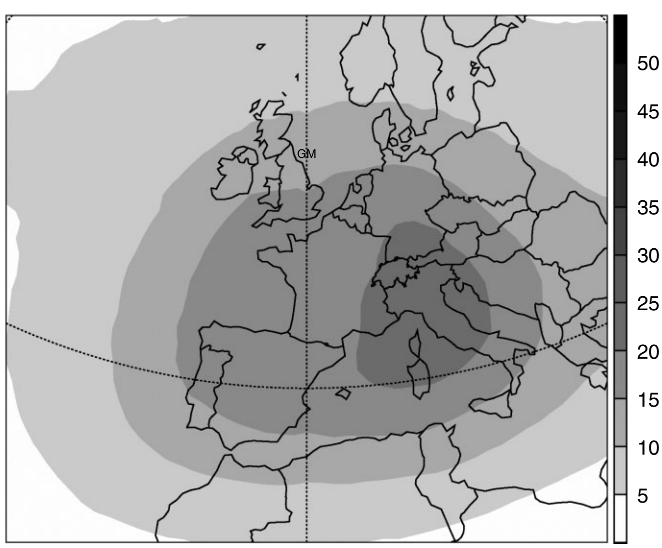

Figure 3. As in Figure 2(a) but for all non-EX10P precipitation days of the 34-year time period

the occurrence of lee-cyclogenesis underlying a streamer cut-off and hence not included in the streamer catalogue. The distinct differences in amplitude, location, and shape between the climatological streamer composite (Figure 2(a)) and the counter composite (Figure 3) are significant and dynamically meaningful.

In effect, they point to the nature of the 'HP-Streamer' linkage. Likewise, the identification of 73% of extreme HP days as streamer situations during the 34-year period points to the strength of that linkage, and the streamer composite's resemblance to the archetypical structures identified in earlier case studies of individual heavy precipitation lends further credence to the linkage.

3.1.2. Sub-domains (Grisons, Valais, Ticino). Now consider the analogue of the frequency composite of Figure 2(a) but for HP days in the three sub-regions of the Grisons, Valais, and the Ticino. Despite their spatial proximity, HP days in the different sub-regions coincide only in about 50% of the cases, and for the other half the extreme precipitation occurs exclusively in only one of the three regions. For example, on 61 of the 124 days of extreme precipitation in TI, the precipitation that fell in the GR or the VS on the same day did not exceed the local threshold criterion.

The frequency composites for the GR (69 days), the TI (61 days) or the VS (69 days) are displayed in Figure 4. There are inter-region differences in shape, location, and orientation. For the GR, the maximum in the streamer frequency is located over southern England and the Channel Islands and is meridionally orientated and zonally confined. For the TI, it is more circular and centred over the north coast of the Iberian Peninsula. For the VS, there are two local maxima, one along the French Atlantic Coast and one over Sardinia, but both are lower in amplitude. The decrease in amplitude is indicative of a larger spatial variability in streamer occurrence.

A measure of the statistical significance of the regional differences in the streamer frequency can be gleaned from Figure 5. (The significance test applied is described in Appendix A and significance was set at the 95% level). Figure 5(a) and (b) indicates a northward shift of the frequency maximum of the GR with respect to that of the TI and the VS, but with a reversal in the relative orientation. This is consistent with the streamers inducing HP in the GR region being located further north with a greater tendency to be meridionally aligned. Likewise, Figure 5(c) hints at the equatorward elongation and NE-SW orientation of TI *versus* VS streamers. The latter is consistent with the secondary frequency maximum over Sardinia in the VS composite that suggests a more frequent NW-SE tilt of the streamers that trigger extreme precipitation in the VS.

3.2. Streamer orientation

The objective composite analysis shown in the previous sub-section hints at a different predilection in the orientation of the streamers. To explore this further, a subjective case-by-case classification of the streamers was undertaken. In line with the identification of different types of cyclogenesis using idealized models (Davies *et al*., 1991; Thorncroft *et al*., 1993), streamers were divided into four categories: (i) LC1-type (anticyclonic) streamers, (ii) meridionally oriented streamers, (iii) LC2-type (cyclonic) streamers, and (iv) streamers with strong curvature or rapidly evolving form. The results are consistent with the earlier inferences and are

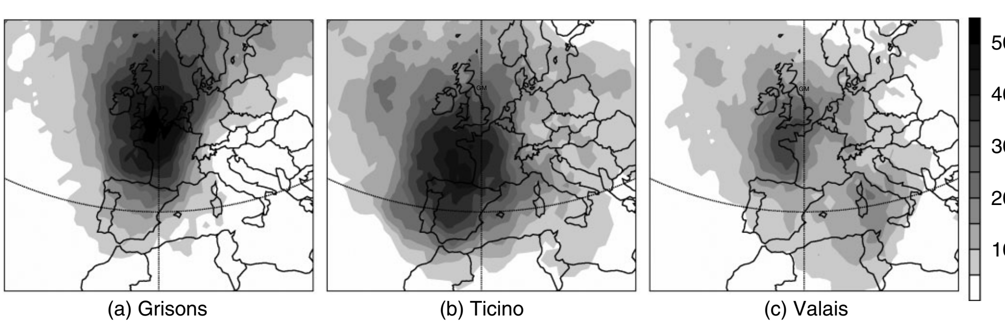

Figure 4. As in Figure 2(a) but for the cases with extreme precipitation in exclusively one of the sub-domains, (a) Grisons, (b) Ticino and (c) Valais

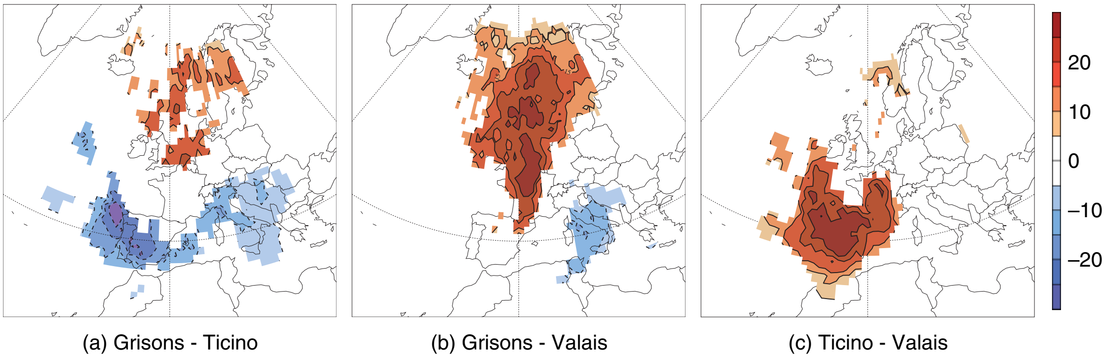

Figure 5. Statistically significant differences (95% sign. level) in the frequency distribution of the respective sub-domains (shaded), contour lines are solid for positive and dashed for negative differences, (a) GR – TI, (b) GR – VS and (c) TI – VS

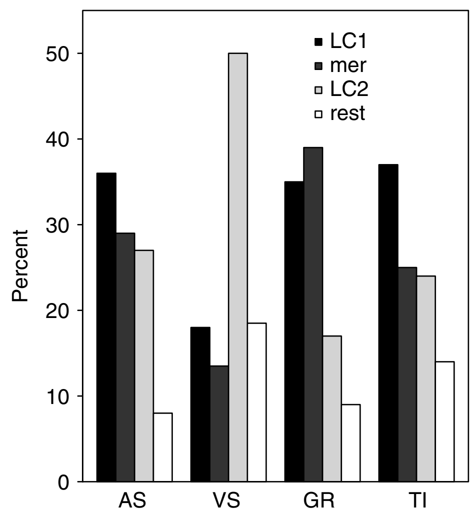

Figure 6. Distribution of the streamer orientation for the different regions. The four categories used are: LC1-type (black), meridional (dark grey), LC2-type (light grey) and the ambiguous rest (white). The percentage is relative to the total number of steamers found for the EX1P days of each region

summarized in Figure 6. AS-related streamers show a slight preference of LC1-type orientation (36%), followed by 28% with meridional direction, and 27% of LC2-type streamers. TI-related streamers show a similar relative distribution. The most striking difference is found between the GR (∼75% LC1 and meridional) and the VS (∼50% LC2). Noting that categories (i) and (ii) are associated with similar cyclogenetic structures, there is some merit in co-grouping these categories and this gives further support to the above diagnosis. A similarly distinct regional separation of preferred orientation was reported by Rudari *et al*. (2004) who detect a clear meridional axis of the 500 hPa troughs associated with extreme rainfall in Tuscany. In summary, the orientation and meridional extent of the streamer appear to exert a significant influence upon the occurrence of HP in a particular region.

4. STREAMER INFLUENCE ON PRECIPITATION

In contrast to the previous section, here we consider explicitly the influence upon the precipitation of the presence of an overlying streamer. Streamers are present over western Europe frequently (i.e. several days per week) and clearly not all of them are associated with HP.

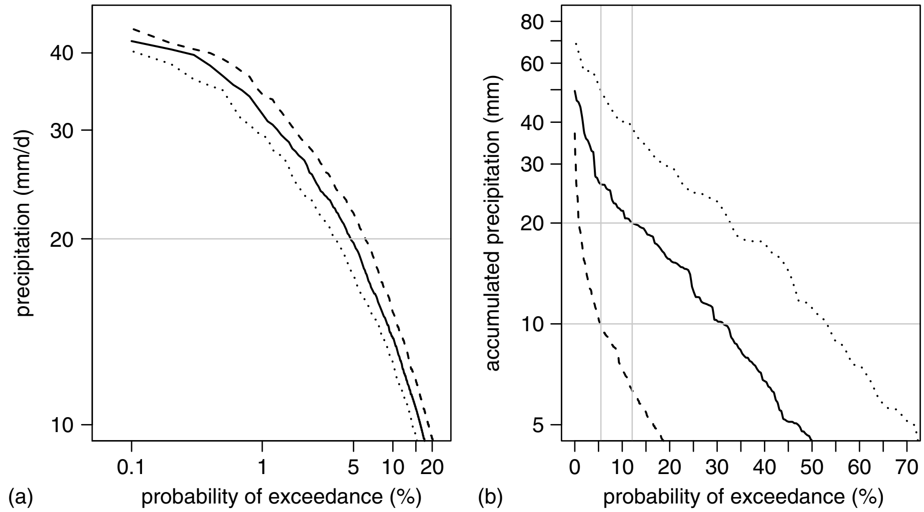

Figure 7. Probability of exceedance for the AS precipitation probability distribution. (a) Mean precipitation distribution (solid line), probability distribution for precipitation days with an upper-level streamer present (dashed line), and for the precipitation days with no streamer present (dotted line). (b) Accumulated precipitation distribution for consecutive streamer days with a persistence of ≤ 1 days (dashed), 1–2 days (solid), >2 days (dotted). Vertical and horizontal lines mark 10 mm and 20 mm intensities and their respective probabilities (see text for details)

For the probability analysis conducted here, the 34-year daily area-averaged (AS) precipitation days are split into two classes corresponding to days with and without a concomitant streamer over western Europe.

4.1. Precipitation probability distribution

The precipitation distributions, displayed in the form of 'probability of exceedance' (POE) curves, are shown in Figure 7(a) for these two classes and for the climatological mean. The POE-plots show the precipitation as a function of the percentage of time that that amount will be attained (or surpassed). Note that the probability values are based on precipitation days only (i.e. rainfall $\geq$0.1 mm/d), and that the probabilities account only for the maximum daily precipitation recorded during the 34-year period (i.e. 51.1 mm/d). Indeed, the distribution is not plotted for daily precipitation amounts higher than 45 mm/d since they occur so rarely (POE $<$ 0.1). Nevertheless, recall that the extreme AS-EX1 category, comprising events of rainfall $\geq$29.1 mm/d, still represented 124 days. Note also that the population of the classes becomes more asymmetric as the precipitation amount increases, since 91 days out of the 124 are streamer days.

The POE curve for the mean climatology of the data set (Frei and Schär, 1998) has been derived and discussed by Frei *et al*. (2003). Figure 7(a) shows that in the presence of an upper-level streamer, the POE is enhanced for all precipitation classes from moderate to heavy. For example, the probability of precipitation of 20 mm/day or more to occur is 3.55% for the no-streamer days, but 6.1% for the streamer cases compared to the climatological mean 4.7%. This corresponds to a relative increase of the precipitation probability by 70% between no-streamer and streamer cases. The curves converge towards the more extreme precipitation amounts owing to sampling problems. In effect, there are fewer events and the population of the no-streamer class becomes very small. For instance, there are 20 events with a precipitation mean of more than 40 mm/day, 15 of which occur concomitantly with an upper-level streamer. It follows that the probability to exceed a certain precipitation threshold is enhanced in the presence of a streamer. The increase in probability is even more evident as higher precipitation amounts are considered. From a vortex-dynamical perspective, this effect could result from a positive feedback mechanism between the cyclonic circulation of the streamer anomaly and the diabatically-enforced downstream upper-level ridge resulting in a strengthened southerly flow component.

4.2. Temporal persistence of the streamers

In principle, longer-lived streamers could yield a more sustained flux of moisture towards the Alps. It is therefore appropriate to investigate the relationship between a streamer's residence in the vicinity of the Alps and the accumulated area-averaged AS precipitation.

This residence time was determined and the previous precipitation analysis repeated for streamers with increasing temporal persistence. Three different persistence times have been considered: (1) a day or less, (2) between one and two days and (3) more than two days. Figure 7(b) shows the accumulated precipitation as a function of the POE for the three different time categories. It follows from the figure that more persistent streamers are associated with higher amounts of accumulated precipitation. The inference is that short-lived streamers do not produce the same net amount of precipitation as longer-lived systems by yielding more intense rainfall over a shorter time period. It also follows from the figure that the longer-lasting streamers are related to disproportionately intense precipitation events. For instance, the precipitation probability of 10 mm/d is more than doubled from streamers that last one day or less (5.5%) compared to streamers with a persistence of one to two days (12.1%).

5. VARIABILITY AND TRENDS

5.1. Seasonal variability and moisture fluxes

There is a marked seasonal variability in the occurrence of extreme Alpine daily precipitation (e.g. Schmidli *et al*., 2002). Likewise, the occurrence, location, and orientation of streamers, and their associated flux of moisture towards the Alpine ridge can be (and is) subject to seasonal variability. It is the nature of and the linkage between this double variation that we explore in this section.

5.1.1. Alpine south side. Inspection of Figure 8 sheds light on this relationship. For AS-EX1P (Figure 8(a)), the largest fraction of the extreme precipitation events occurs in autumn (SON, 44%), while only very few happen during the winter months (DJF, 8%). The rest is equally split between the spring (MAM) and the summer (JJA) season. The corresponding seasonal sub-division in the number of streamers recorded during

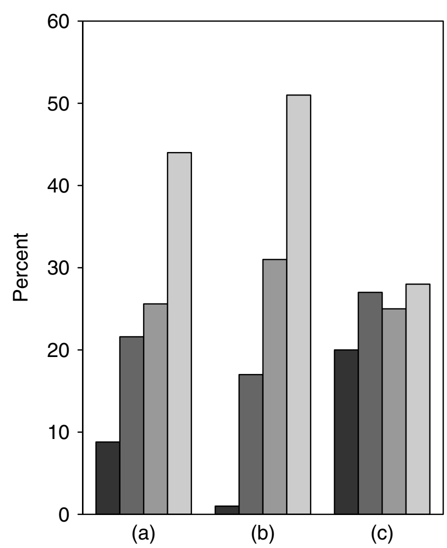

Figure 8. (a) The seasonal distribution of the 124 AS-EX1P precipitation days (%), (b) the seasonal distribution of the 91 AS-EX1P precipitation days, where a streamer is present (%), and (c) the climatological seasonal streamer frequency over Europe (%) for all 8340 streamer days. Shading indicates the four seasons winter (dark grey), spring (medium grey), summer (light grey) and autumn (lightest grey)

Table I. For extreme (AS-EX1P, top) or heavy (AS-EX5P, bottom) precipitation, columns display the number of days (and percentages relative to the no-streamer count) of respectively (1) all autumn HP events and (2) days without an upper-level streamer, which include (3) broad troughs, (4) stratospheric cut-offs, and (5) remaining cases without a clear upper-level signature

Case	Autumn HP events	No-streamer (%)	Broader trough (%)	Cut-off (%)	Remainder (%)
AS-EX1P	55	8 (100)	4 (50)	2 (25)	2 (25)
AS-EX5P	212	38 (100)	21 (55)	6 (16)	11 (29)

HP events (Figure 8(b)) is not distributed evenly with the seasons. A larger fraction (51%) occurs in the autumn season, with summer and spring accounting for most of the rest. Comparison of Figure 8(a) and (b) suggests that (1) the seasonal differences in contemporaneous occurrence is more pronounced (however, the two populations correspond to different base samples), and more pointedly that (2) the relative probability of HP days in autumn is increased in the presence of streamers. Note in passing that the same conclusions emerge when HP (AS-EX5P) is considered (not shown). However, the analogue sub-division for the actual number of streamer occurrences (Figure 8(c)) shows far less of a seasonal variation, with little variation from spring through to autumn but a reduction in winter. Thus, the role of streamers in instigating HP days is modulated by other factors.

Here, we seek to gain some insight into these other factors. First, we determine the nature of the upper-level flow for the autumnal extreme and HP days (AS-EX1P, AS-EX5P) devoid of an upper-level streamer (Table I for details). For instance, half of the AS-EX5P non-streamer days are accounted for by a broad trough present at upper-levels. The zonal extent of these troughs is too wide to be classified as a streamer by the detection routine. Another sixth are associated with a cut-off over southwestern Europe. It is particularly noteworthy that both features can, and often are, linked with a southerly surface flow field. For the remaining cases, no distinct upper-level PV-anomaly was discernible.

Secondly, we examine the nature of the large-scale moisture flux impinging upon the Alps. This is prompted, for example, by the dichotomy in the frequency distributions of the HP days and upper-level streamers between summer and autumn. There is only a small change in the total streamer frequency in spring, summer and autumn, but a higher proportion of streamers are associated with HP in autumn than in other seasons. A possible factor is the difference in the corresponding, prevailing humidity distribution and hence its influence upon the incident moisture flux. For all streamer days, regardless of the precipitation amount, the vertically-integrated net horizontal moisture flux (IMF) of a 34-year period across the southern boundary of the AS box is evaluated (*cf.* Section 2), and shown to have a strong seasonal variation (Figure 9(a)). The mean of the net fluxes is positive only in autumn. An oppositely directed mean flux prevails in the other seasons particularly in winter. It can also be gleaned from this figure that very strong positive moisture fluxes are more frequent in autumn than in spring. For instance, for the mean net moisture flux of the AS-EX1P days ($\sim 5^{*}10^{6}$ g_{H20}/m^2, *cf.* Figure 9(b)), the total number of counts in this class consists mainly of contributions from autumn (38) and summer (31), while winter (1) and spring (18) are less important. The significance of this seasonal moisture flux variation is evident on noting that a northerly flow would generally connote an alpine overflow with descending air on the lee south side. For streamers, such a result would prevail if they reside longer to the east, rather than the west of the Alps. Contrariwise, the autumnal southerly flux is consistent with the occurrence of streamer-related precipitation. The difference in the moisture flux between spring and autumn seasons, when the occurrence of suitably located streamers are equally likely, could arise either from the subsequent movement (or lack of) the streamers, or be linked to the warmer sea-surface temperatures of the Atlantic and the Mediterranean in autumn (Doswell *et al.*, 1998), giving rise to a higher capacity to moisten the lower layers of the atmosphere.

5.1.2. Sub-domains (Grisons, Ticino, Valais). An inspection of the seasonal variability in the sub-regions reveals interesting differences (Table II). However, the significance of the following observations is debatable

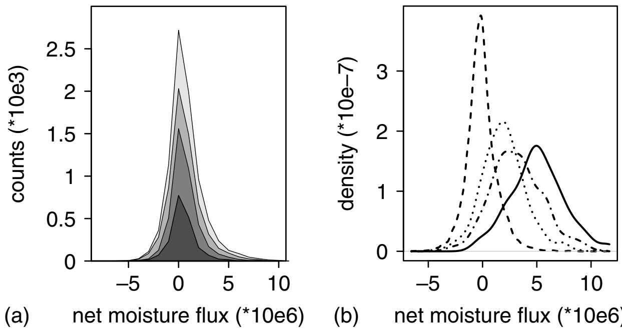

Figure 9. (a) Histogram of net moisture flux across the southern AS boundary on all streamer days. Moisture flux in (10^6 g_{H20}/m^2), bin size is 10^6 g_{H20}/m^2. Total counts are partitioned according to the season, winter (dark grey, mean value 0.055), spring (medium grey, mean value −0.042), summer (light grey, mean value −0.088), autumn (lightest grey, mean value −0.16). (b) Probability density functions (10^{-7} m^2/g_{H20}) of the recorded daily net moisture flux across the southern AS boundary for the different HP classes: AS-EX1P (solid, mean value 5.06), AS-EX5P without AS-EX1P (dash-dotted, 3.16), AS-EX10P without AS-EX5P (dotted, 1.96), all non-AS-EX10P (dashed, −0.92)

Table II. Seasonal distribution of the extreme precipitation in the three sub-domains GR, TI, VS and seasonal distribution of the link between extreme precipitation and streamer occurrence in counts, in 34 years and in brackets the percentage of total counts of each row. These percentages are directly comparable to those in Figure 8(a) and (b)

Region		Winter (%)	Spring (%)	Summer (%)	Autumn (%)
GR-EX1P	Rain	0 (0)	10 (14.5)	35 (50.7)	24 (34.8)
	Rain + Streamer	0 (0)	7 (14)	25 (50)	18 (36)
TI-EX1P	Rain	11 (18)	18 (29.5)	6 (9.8)	26 (42.6)
	Rain + Streamer	0 (0)	14 (32.5)	5 (11.7)	24 (55.8)
VS-EX1P	Rain	22 (31.8)	16 (23.2)	3 (4.4)	28 (40.6)
	Rain + Streamer	0 (0)	10 (32.3)	3 (9.7)	18 (58)

because of the small sample sizes that arise from the seasonal splitting. In the GR summer, HP events dominate and the seasonal frequency distribution does not change in the presence of streamers. For the TI, it is obvious that summer HP events have no relation to the occurrence of streamers, but must be caused by other processes such as local convection, while autumn events become more frequent than spring events as is also observed in the AS cases. In the VS, this relative increase associated with the streamers is less prominent. Of the three sub-domains, winter events in this HP class are only recorded for the VS.

5.2. *Severity of precipitation events*

From a forecasting perspective, it would be helpful to be able to distinguish between streamers associated with extreme (AS-EX1P) as opposed to merely heavy (AS-EX5P, AS-EX10P) precipitation events. A climatological equivalent is required of the kind of case-study analyses conducted by Fehlmann and Quadri (2000) and Fehlmann *et al*. (2000), who investigated the mesoscale structure of the upper-level feature and the sensitive regions of the latter for the forecast of HP in the Alps. Subjective analysis of the form and the location of streamers in the AS-EX1P category compared with those associated with the AS-EX5P category showed no apparent systematic and unambiguous difference. The mean amplitude of AS-EX1P streamers was 0.4 pvu larger than that of the AS-EX5P streamers and this amounts to a non-significant difference for the two distributions, however, the shape of the amplitude distribution curves is distinctly dissimilar for the two samples (not shown). For the extreme AS-EX1P category, the distribution is skewed heavily to higher amplitudes. It suggests that extreme events are associated with a streamer PV maximum of $>\sim 5$ pvu, which is

~2 pvu larger than for the climatological sample, and a significant number of streamers exist with amplitudes ~8–10 pvu, which do not occur for other HP severity classes.

However, the moisture flux appears to be the major factor distinguishing precipitation severity (Figure 9(b)). Large differences can be observed in the distributions of the net moisture fluxes across the southern AS boundary on streamer days for four event classes of increasing severity. The mean southerly moisture flux of the AS-EX5P sample not including the AS-EX1P precipitation days (i.e. 'AS-EXP2-5P') amounts to only two-thirds of the mean moisture flux on the AS-EX1P days, and the 'AS-EX6-10P' moisture flux is another 30% smaller than on the 'AS-EX2-5P' days. Notably, the mean southerly flux of those days excluding AS-EX10P days is more than an order of magnitude smaller than AS-EX1P fluxes. Thus, the severity of the streamer-related AS precipitation does depend sensitively on the availability of moisture.

5.3. *Trends*

In this sub-section, tentative estimates are derived for trends in the different streamer-related variables during the 34-year investigation period. (This short time span argues against being able to attribute a large significance to the estimates). There have been numerous previous studies of Alpine precipitation trends. For example, a trend study for extreme precipitation events in Switzerland over the last century (1901–1994) showed a statistically significant increase of intense precipitation (30 d return period) in autumn and winter (Frei and Schär, 2001), whereas the trends for strong events (100 d return period) were not statistically significant except at a few stations. Recently, their results have been complemented and confirmed by a trend analysis of a multitude of statistical measures in an extended data set (1901–2000, Schmidli and Frei, 2005). An analysis for the 1961–1990 period that is comparable to the one considered here shows a positive precipitation trend in spring for the TI and a significant negative trend in northern Italy in autumn (Widmann and Schär, 1997; Schmidli *et al.*, 2002).

In line with and prompted by the above studies, we examine separately and in combination the trends associated with our streamer and HP precipitation climatologies. A standard t-test method was applied for several significance levels (99%, 95%, and 90%) and for all three severity categories. Note that the small number of events in the AS-EX1P sample renders testing for trends extremely difficult (e.g. Frei and Schär, 2001).

For the 1966–1999 precipitation-only climatology in the AS region, a positive but non-significant trend was detected in the number of events for all three HP precipitation categories. Likewise, the streamer climatology shows no significant trend in the total number of streamer events over Europe per year. For the combined streamer-related HP events, the trend in intensity was also not significant. However, the yearly frequency of streamer-related HP exhibits positive trends: AS-EX1P (non-sig.), AS-EX5P (95% sig.), AS-EX10P (non-sig.). These results are corroborated by the century-long precipitation trend analysis of Schmidli and Frei (2005) who find positive and also significant trends for several HP measures (e.g. EX10P and EX5P equivalents), especially in the TI and GR region.

It is pertinent to note that a positive trend was detected for the southerly moisture flux towards the Swiss Alps for all three categories: AS-EX1P (90% sig.), AS-EX5P (90% sig.), AS-EX10P (non-sig.). These trends could arise from an increased atmospheric moisture content, enhanced surface winds (and reduced stability) or their combination. The first effect would in turn be linked to the atmospheric temperature increase observed over the last century (e.g. Houghton *et al.*, 2001). Further indications of this 'moisture effect' can be gleaned from a study by Frei *et al.* (1998) on heavy Alpine autumn precipitation in a warmer and moister climate. With regional climate modelling experiments, they also conclude that the regional hydrological cycle is intensified, reflected in significant changes in the precipitation intensity distribution and reduced return periods of strong events.

In summary, the analysis reveals that the number and intensity of streamers over Europe did not increase significantly over the last three decades, but the ability of a PV-streamer to contribute to HP (AS-EX5P) appears to have changed this may be in part linked to a significantly positive trend in the southerly moisture fluxes.

6. FURTHER ISSUES

Here, we consider a variety of further issues related to the 'HP-Streamer' linkage. A first issue relates to the large-scale flow structure that spawns a streamer. Case studies (Massacand *et al*., 2001) and cluster analysis (Plaut *et al*., 2001) suggest that a major upstream ridge accompanies the formation of a streamer. Support for this hypothesis can be gleaned from the inspection of Figure 2(b) since there is a prominent low-PV ridge upstream over the eastern Atlantic in the isentropic PV composite for these AS-EX1P streamers, and intense diabatic processes can contribute to inducing low values of upper-level PV. This issue merits further climatological and dynamical studies. The aforementioned coherent upstream signal of the isentropic PV composite is clearly a salient feature, and we plan to extend our analysis to look for precursor signals for the streamers situated even further upstream.

A second point is the linkage, if any, of streamers to the large-scale teleconnection patterns. For the time period under investigation, the NAO was predominantly in its positive phase and steadily increasing (*cf*. Hurrell (1995) and references therein). The associated flow field and its evolution over the Atlantic is related to characteristic sea-surface temperature, surface wind fields, precipitation, and large-scale moisture flux patterns (Hurrell, 1995). These could in turn influence the spatial and temporal patterns of the occurrence of streamers (Franzke *et al*., 2004).

A further issue is to link the trend for streamer-related AS-EX5P events to a compelling causatory mechanism. Possible factors would be the form of the streamers (LC1 or LC2), their elongation and/or location. For example, an elongated streamer located further equatorward is also more likely to penetrate closer towards the surface and thereby increase its HP-inducing potential.

The final remarks pertain to the limited observational evidence on the location and substructure of the streamers. A combination of several data sources, such as a water-vapour DIAL, O3-lidar, satellite information and additional NWP analysis fields and techniques (RDF), is required in detailed case studies to interpret the mesostructure of stratospheric streamers (*cf*. for Alpine streamers e.g. Hoinka *et al*. (2003); Liniger and Davies (2003) and references therein).

7. SUMMARY AND CONCLUDING REMARKS

This study sought to examine from a climatological standpoint the relationship between HP along the Alpine south side and upper-level streamers over western Europe. The examination was based on a comparison of a 34-year daily Alpine precipitation climatology with a corresponding upper-level streamer climatology. In particular, the occurrence of upper-level streamers on HP days was examined for a band along the Alpine south side and three Alpine sub-regions. The dynamical link between the two phenomena, postulated upon the basis of previous case-study analyses, is supported by the results of the climatological study. For example, on 73% of the EX1P days, an upper-level streamer was present over western Europe for the Alpine south side and for the different sub-regions. The link is most evident in autumn when a streamer is present on more than 85% of the HP days, and it is weakest in winter when the corresponding figure is only 30%.

Both frequency and physical composite of the upper-level streamers over western Europe on the AS-EX1P days (91 streamers on 124 HP days) have a spatial structure resembling the archetypal streamer identified in case studies. HP days in the three sub-regions are accompanied by streamers with distinctive forms and locations. Streamers associated with HP along the whole Alpine south side are equally distributed over the three classes of orientation (LC1-type, LC2-type, and meridional alignment). Grison-related streamers are shifted northwards and possess a predominantly meridional orientation. Valais-related streamers show two frequency maxima, one over England and one over the Mediterranean and the majority possesses an LC2-type orientation. Ticino-related streamers extend further south than the others and are often oriented in an LC1-type fashion.

Streamers of longer temporal persistence are associated with precipitation of stronger intensity. Moreover, the incident moisture is a key factor distinguishing the severity of HP events (e.g. AS-EX1P and the AS-EX5P categories), and also exerts an important influence on the seasonal variation of streamer-related HP events. The autumnal peak of the latter is because of enhanced moisture fluxes and the frequent occurrence of streamers in that season. Thus, in addition to providing climatological support for the link between HP events and streamers that was originally gleaned from case-study analyses, the inter-relationships derived in the present study also provide motivation for conducting further diagnostic dynamical studies.

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APPENDIX A

Testing the significance of the differences between two binomially distributed fields

To find significant differences in the streamer frequency distribution between two sub-domains, we perform the following test at each grid-point of the composite fields. Since the frequencies are compiled from binary fields, we assume the streamer frequency of both fields (A,B) to be binomially distributed. The streamer frequency is estimated for each field (Equation (1)) using the mean probability of both fields (Equation (2)). Then the difference is taken between the two estimated frequencies (Equation (3)).

$$f_{na,b} = binom(p_{nm}, N_{a,b}) \tag{1}$$

n indicates the grid-point, a and b the individual fields, N is the number of streamer events

$$p_{nm} = \frac{(p_{na} + p_{nb})}{2} \tag{2}$$

$$f_{ndiff} = f_{na} - f_{nb} \tag{3}$$

This calculation is repeated 100 times to obtain a density distribution of the difference. We can test now if the observed difference lies within the extremest 5% of the aforementioned simulated distribution. Differences smaller than 5% and larger than 95% are marked significant.

REFERENCES

Appenzeller C, Davies HC. 1992. Structure of Stratospheric intrusions into the Troposphere. *Nature* **385**: 570–572.

Bougeault P, Binder P, Buzzi A, Dirks R, Houze R, Kuettner J, Smith RB, Steinacker R, Volkert H. 2001. The MAP special observing period. *Bulletin of the American Meteorological Society* **82**: 433–462.

Buzzi A, Tartaglione N, Malguzzi P. 1998. Numerical simulations of the 1994 Piedmont flood: Role of orography and moist processes. *Monthly Weather Review* **126**: 2369–2383.

Davies HC, Schär C, Wernli H. 1991. The palette of fronts and cyclones within a Baroclinic development. *Journal of the Atmospheric Sciences* **48**: 1666–1689.

Doswell CA, Ramis C, Romero R, Alonso S. 1998. A diagnostic study of three heavy precipitation episodes in the western Mediterranean region. *Weather and Forecasting* **13**: 102–124.

Fehlmann R, Quadri C. 2000. Predictability issues of heavy Alpine south-side precipitation. *Meteorology and Atmospheric Physics* **72**: 223–231.

Fehlmann R, Quadri C, Davies HC. 2000. An Alpine rainstorm: Sensitivity to the mesoscale upper-level structure. *Weather and Forecasting* **15**: 4–28.

Franzke C, Lee S, Feldstein SB. 2004. Is the North Atlantic oscillation a breaking wave? *Journal of the Atmospheric Sciences* **61**: 145–160.

Frei C, Schär C. 1998. A precipitation climatology of the Alps from high-resolution rain-gauge observations. *International Journal of Climatology* **18**: 873–900.

Frei C, Schär C. 2001. Detection probability of trends in rare events: Theory and application to heavy precipitation in the Alpine region. *Journal of Climate* **14**: 1568–1584.

Frei C, Schär C, Lüthi D, Davies HC. 1998. Heavy precipitation processes in a warmer climate. *Geophysical Research Letters* **25**: 1431–1434.

Frei C, Christensen JH, Déqué M, Jacob D, Jones RG, Vidale PL. 2003. Daily precipitation statistics in regional climate models: Evaluation and intercomparison for the European Alps. *Journal of Geophysical Research* **108**: D34124, DOI:10.1029/2002/D002287.
Gheusi F, Davies HC. 2004. Autumnal precipitation distribution on the southern flank of the Alps: A numerical-model study of the mechanisms. *Quarterly Journal of the Royal Meteorological Society* **130**: 1–28.
Hoinka KP, Richard E, Poberaj G, Busen R, Caccia JL, Fix A, Mannstein H. 2003. Analysis of a potential-vorticity streamer crossing the Alps during MAP IOP 15 on 6 November 1999. *Quarterly Journal of the Royal Meteorological Society* **129**: 609–632.
Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D. 2001. IPPC Third Assessment Report: Climate Change 2001, The Scientific Basis. Intergovernmental Panel on Climate Change.
Houze RA, James CN, Medina S. 2001. Radar observations of precipitation and airflow on the Mediterranean side of the Alps: Autumn 1998 and 1999. *Quarterly Journal of the Royal Meteorological Society* **127**: 2537–2558.
Hurrell JW. 1995. Decadal Trends in the North-Atlantic Oscillation – Regional Temperatures and Precipitation. *Science* **269**: 676–679.
Jacobeit J. 1987. Variations of trough positions and precipitation patterns in the Mediterranean area. *Journal of Climatology* **7**: 453–476.
Koch P. 2004. Novel perspectives of jet-stream climatologies and events of heavy precipitation on the alpine southside. PhD thesis. ETH Zurich. Diss. ETH No 15 622.
Lanzinger A. 1992. Upper and lower level PV-coupling. *Meteorologische Zeitschrift* **1**: 173–181.
Liniger MA, Davies HC. 2003. Substructure of a MAP streamer. *Quarterly Journal of the Royal Meteorological Society* **129**: 633–651.
Liniger MA, Davies HC. 2004. Seasonal differences in extratropical potential vorticity variability at tropopause levels. *Journal of Geophysical Research* **109**: D17102, DOI:10.1029/2004JD004639.
Massacand AC, Wernli H, Davies HC. 1998. Heavy precipitation on the Alpine southside: An upper-level precursor. *Geophysical Research Letters* **25**: 1435–1438.
Massacand AC, Wernli H, Davies HC. 2001. Influence of upstream diabatic heating upon an Alpine event of heavy precipitation. *Monthly Weather Review* **129**: 2822–2828.
Plaut G, Simonnet E. 2001. Large-scale circulation classification, weather regimes, and local climate over France, the Alps and Western Europe. *Climate Research* **17**: 285–302.
Plaut G, Schuepbach E, Doctor M. 2001. Heavy precipitation events over a few Alpine sub-regions and the links with large-scale circulation, 1971–1995, *Climate Research* **17**: 285–302.
Reale O, Feudale L, Turato B. 2001. Evaporative moisture sources during a sequence of floods in the Mediterranean region. *Geophysical Research Letters* **28**: 2085–2088.
Romero R, Summer G, Ramis C, Genovés A. 1999. A classification of the atmospheric circulation patterns producing significant daily rainfall in the Spanish Mediterranean area. *International Journal of Climatology* **19**: 765–785.
Rudari R, Entekhabi D, Roth G. 2004. Terrain and multiple-scale interactions as factors in generating extreme precipitation events. *Journal of Hydrometeorology* **5**: 390–404.
Rudari R, Entekhabi D, Roth G. 2005. Large-scale atmospheric patterns associated with mesoscale features leading to extreme precipitation events in Northwestern Italy. *Advances in Water Resources* **28**: 601–614.
Schmidli J, Frei C. 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. *International Journal of Climatology* **25**: 753–771.
Schmidli J, Schmutz C, Frei C, Wanner H, Schär C. 2002. Mesoscale precipitation variability in the region of the European Alps during the 20th century. *International Journal of Climatology* **22**: 1049–1074.
Simmons AJ, Gibson JK. 2000. The ERA-40 Project Plan. Technical report: ECMWF Shinefield Park Reading UK.
Simonnet E, Plaut G. 2001. Space-time analysis of the geopotential height and SLP, intraseasonal oscillations, weather regimes, and local climates over the North Atlantic and Europe. *Climate Research* **17**: 325–342.
Thorncroft CD, Hoskins BJ, McIntyre MF. 1993. Two Paradigms of Baroclinic-Wave Life-Cycle Behavior. *Quarterly Journal of the Royal Meteorological Society* **119**: 17–55.
Turato B, Reale O, Siccardi F. 2004. Water vapor sources of the October 2000 Piedmont flood. *Journal of Hydrometeorology* **5**: 693–712.
Wernli H, Sprenger M. 2005. Identification and ERA-15 climatology of potential vorticity streamers and cut-offs near the extratropical tropopause, submitted to JAS.
Widmann M, Schär C. 1997. A Principal Component and long-term Trend Analysis of the Daily Precipitation in Switzerland. *International Journal of Climatology* **17**: 1333–1356.

