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Spatial and temporal analysis of fatal off-piste and backcountry avalanche accidents in Austria with a comparison of results in Switzerland, France, Italy and the US

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Abstract. In this article we analyzed spatial and temporal patterns of fatal Austrian avalanche accidents caused by backcountry and off-piste skiers and snowboarders within the winter periods 1967/1968–2015/2016. The data were based on reports of the Austrian Board for Alpine Safety and reports of the information services of the federal states.

Using the date and the location of the recorded avalanche accidents, we were able to carry out spatial and temporal analyses applying generalized additive models and Markov random-field models.

As a result of the trend analysis we noticed an increasing trend of backcountry and off-piste avalanche fatalities within the winter periods 1967/1968–2015/2016 (although slightly decreasing in recent years), which is in contradiction to the widespread opinion in Austria that the number of fatalities is constant over time. Additionally, we compared Austrian results with results of Switzerland, France, Italy and the US based on data from the International Commission of Alpine Rescue (ICAR). As a result of the spatial analysis, we noticed two hot spots of avalanche fatalities ("Arlberg–Silvretta" and "Sölden").

Because of the increasing trend and the rather "narrow" regional distribution of the fatalities, initiatives aimed at preventing avalanche accidents were highly recommended.

1 Introduction

In the Alps, backcountry skiing has become very popular in the last 50 years. Unfortunately, there are a lot of fatal accidents due to snow avalanches caused by skiers and/or snowboarders. They are of special public interest (Januskovecz, 1989).

In Austria, about 25–30 fatalities caused by snow avalanches are expected every year (Neuhold, 2012; Höller, 2009). Furthermore, it is reported that in Alpine countries (such as Austria) the number of fatalities is more or less constant over the time (Brugger et al., 2001; Valt and Pivot, 2013; Roth, 2013) and that there is some sort of seasonality in the data in terms of higher frequencies of accidents within a distance of 5 or 6 years (Höller, 2009; Tschirky et al., 2000). Harvey and Zweifel (2008) even denote that fatalities are decreasing over time in Switzerland. In a recent paper Techel et al. (2016) investigated avalanche fatalities in the European Alps (in addition to Switzerland–Austria–Slovenia) over time stratified for controlled and uncontrolled terrain, concluding that in the case of uncontrolled terrain the trend seems to be constant over time from the 1980s up to now.

Usually trend information for Austrian avalanche fatalities is given in the annual reports of the Austrian Board for Alpine Safety (Kuratorium für alpine Sicherheit, 1973–2016). Considering these profiles, we notice higher frequencies of fatalities in the 1980s. However, the highest frequency, in winter 1998/1999, is due to avalanche fatalities in villages (Galtür, Ischgl), also affecting buildings. This is because the statistics in the reports do not distinguish between fatal avalanches in buildings, on roads and outdoors without skiing, and fatalities due to skiing on slopes and backcountry skiing.

In this paper our focus is on accidents caused by backcountry (using no ascent support) and off-piste ("leaving the ski resort in order to travel in areas that were not controlled for avalanches"; see Silverton et al., 2009) skiers or snowboarders. We addressed this special group of accidents (backcountry and off-piste avalanche fatalities up to 2010/2011) for the first time in a short paper; see Pfeifer et al. (2013). Most recently, Höller carried out an investigation of backcountry and off-piste avalanche fatalities, stating that there is no significant trend (but a slight change) in the number of deaths (Höller, 2017).

Our task in this paper is to carry out a spatial and temporal analysis, identifying (potentially nonlinear) trends over time and regional patterns. In the case of trend analysis, we compare Austrian results with results of Switzerland, France, Italy and the US.

2 Materials and methods

2.1 Data

For our study we built a database of fatal avalanche accidents recording the

1. date,
2. municipal area where the accident took place,
3. federal state of the municipality,
4. number of persons involved,
5. number of fatalities,
6. type of activity (on/off-piste, backcountry skiing etc.)

of fatal accident events in Austria within the winter periods 1980/1981–2015/2016, which are available from the annual reports of the Austrian Board for Alpine Safety (Kuratorium für alpine Sicherheit, 1973–2016) and the annual reports of the information services of the federal states (Amt der Tiroler Landesregierung, 1994–2009). In order to check the reliability of the accident data, we performed a cross-check between those reported in the two sources. Looking at winter season 1986/1987, we figured out that the reports were incomplete. However, we were able to fill this gap using records of the BFW (Austrian Research Centre for Forests, Institute for Natural Hazards, Innsbruck); see, for example, Schaffhauser (1988).

For the period 1967/1968–1979/1980 we used aggregated information published in the annual reports of the Austrian Board for Alpine Safety (Kuratorium für alpine Sicherheit, 1973–2016). Starting from 1977/1978 we were able to distinguish between backcountry and off-piste fatalities. Finally, further annual reports of the BFW were helpful in order to resolve classification problems of avalanche events.

Keeping in mind aspects of data quality, it seems to be that avalanche information back to the period 1967/1968 is reliable for our purposes. In general information relating to fatal avalanches seems to be much more reliable than information relating only to avalanches with injured or uninjured persons. Most notably, in the case of fatal avalanches we do not expect that there are records missing.

In order to compare Austrian results with international results, we use data from the International Commission of Alpine Rescue (ICAR) which were kindly made available for us by the ICAR.

The data are annual count data of fatal avalanche events (Statistique d'accidents d'avalanche) based on 21 countries within the period 1983/1984–2015/2016, which are categorized by the type of fatalities (backcountry skiing or snowboarding, off-piste, on-piste, alpinist without ski/snowboard, on road, buildings, snowmobile, other).

In the case of the international data (Switzerland: Frank Techel, Auszug aus der Schadenlawinendatenbank des SLF (SLF, 2017); Italy: Mauro Valt, Associazione Interregionale Neve e Valanghe, Trento; France: Frederic Jarry, Association Nationale pour l'Étude de la Neige et des Avalanches; US: Ethan Greene, Colorado Avalanche Information Center) a cross-check was carried out.

For the purpose of looking at the regional distribution of avalanche fatalities, we built small-area maps based on Austrian municipalities. For this purpose we use polygon boundaries of the small-scaled areas provided by the "Bundesamt für Eich- und Vermessungswesen" (BEV) in a shapefile. In order to get a regional overview of the alpine terrain (≥ 1500 m a.s.l. – meters above sea level) for discussion, we use digital elevation model (DEM) data from the BEV at a 250 m resolution. Further on, we use data of overnight stays in the winter season 2015/2016 at community level provided by the "Statistik Austria" as an additional approach for discussion (https://www.statistik.gv.at/web_de/statistiken/wirtschaft/tourismus/beherbergung/ankuenfte_naechtigungen/index.html).

2.2 Statistical methods

After aggregating the spatiotemporal data y_{st} (denoting the observed fatalities at time t and location s) in terms of location, which means summing up over the locations, $\sum_{\mathrm{s}} y_{\mathrm{st}}$, we propose the following model for capturing the trend over time:

$$\log(\mu_t) = f(t) + x_t, \tag{1}$$

where μ_t denotes the expectation of the Poisson distributed number of annual avalanche fatalities over time t (in our case: winter periods). The logarithms of these values are modeled

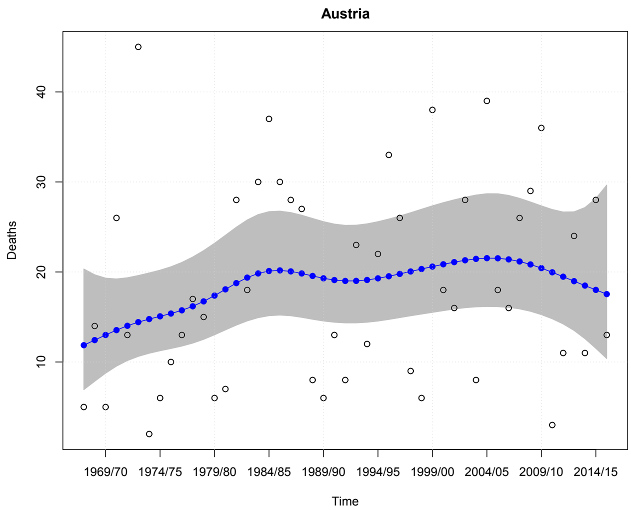

Figure 1. Observed (°) and estimated (•) annual total avalanche fatalities (off-piste and backcountry) with 90 % confidence band (grey) in Austria within 1967/1968–2015/2016.

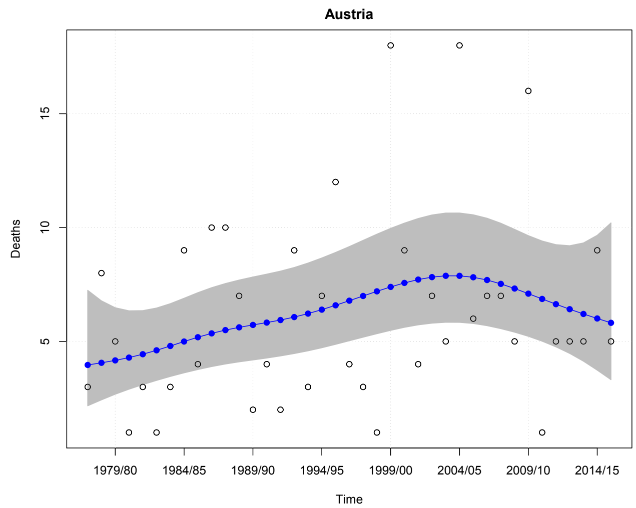

Figure 2. Observed (°) and estimated (•) annual off-piste avalanche fatalities with 90 % confidence band (grey) in Austria within 1977/1978–2015/2016.

as the sum of potentially nonlinear trend function $f(t)$ and a stationary remainder x_t. We use the Aikake information criterion (AIC) and the Bayesian information criterion (BIC) in order to compare the constant, linear and nonlinear model (which is in our opinion a better choice than reporting pairwise comparisons of p values for potentially nonparametric trend functions; see, for example, Venables and Ripley, 2002). To account for potential serial correlation and periodic variation in the remainder, we consider autoregressive moving-average (ARMA) effects.

After aggregating the spatiotemporal data y_{st} in terms of time, which means summing up over the time, $\sum_t y_{\mathrm{st}}$, we propose a Markov random-field approach modeling the expected number of avalanche fatalities μ_{s} (s, $s \in \{1, \ldots, S\}$, denoting the region which are municipalities in our case) as follows:

$$\log(\mu_s) = \mathbf{Z}_s \boldsymbol{\beta} \tag{2}$$

where the $S \times S$ design matrix $\mathbf{Z}$ (and the sth row $\mathbf{Z}_s$ of the design matrix) depends on the specific form of the spatial layout. The coefficients β_s are conditionally Gaussian distributed (Markov random fields) according to

$$\beta_s | \boldsymbol{\beta}_{-s} \sim N\left\{\frac{1}{n_s}\sum_{r\sim s}\beta_r, \frac{\tau^2}{n_s}\right\}, \tag{3}$$

where $\boldsymbol{\beta}_{-s}$ denotes the vector of parameters without its sth component, n_s is equal to the number of neighboring regions with reference to region s, $s \sim r$ indexes all units adjacent to region s and τ^2 denotes a (unknown) variance parameter.

To fit these models, we use the `R` package `mgcv` (R Development Core Team, 2012; Wood, 2006), which applies the smoothing spline approach for fitting generalized additive models (GAM).

Further on, in order to look at the regional distribution of avalanche fatalities (and subsequently at the regional distribution of alpine terrain and overnight stays), we build small-area maps based on Austrian municipalities using the geographic information system (GIS) `ArcMap`. We, of course, use Markov random-field estimates as described above, which helps us to identify regional hot spots of avalanche fatalities.

3 Results

3.1 Temporal results

In the following, we give the plots of estimated temporal functions of avalanche fatalities, at first plotting the function for Austria in total within the winter periods 1967/1968–2015/2016 (see Fig. 1). Additionally, we plot the trend function of exclusively off-piste fatalities starting from the winter season 1977/1978 (see Fig. 2). Further on, we calculate 90 % confidence bands of the estimated functions in both cases as shown in the plots.

For the sake of comparison, Table 1 gives the frequencies of backcountry, off-piste and total fatalities of Austria and neighboring countries Italy and Switzerland within the winter period 1983/1984–2015/2016. Additionally, the off-piste percentages are reported. Furthermore, we report the results of fatalities in France, which turns out to be the country with the highest counts of fatalities in Europe, and the results of the US, which is probably the most important country outside of Europe in terms of avalanche fatalities. For this purpose, however, we use ICAR data as described above.

Table 1. Number of avalanche fatalities and annual average (off-piste, backcountry and total) of five countries within the winter periods 1983/1984–2015/2016.

Country	Backcountry		Off-piste		Total		% off-piste
	Number	Per year	Number	Per year	Number	Per year	
Austria	458	13.88	222	6.73	680	20.61	32.65 %
Switzerland	395	11.97	222	6.73	617	18.70	35.98 %
France	433	13.12	354	10.73	787	23.85	44.98 %
Italy	322	9.76	138	4.18	460	13.94	30.00 %
Sub-total	1608	48.73	936	28.36	2544	77.09	36.79 %
US	201	6.09	83	2.52	284	8.61	29.23 %

Table 2. AIC and BIC of the constant, linear and nonlinear trend model considering data of Austria total and off-piste (Figs. 1 and 2); Switzerland total and off-piste (Fig. 3); France total and off-piste (Fig. 4); Italy total and off-piste (Fig. 5); summing-up of AUT, CHE, FRA and ITA total and off-piste (Fig. 7); and US total and off-piste (Fig. 6).

		Total			Off-piste		
		const	linear	nonlin.	const	linear	nonlin.
Austria	AIC	550.87	543.14	530.30	241.35	238.17	236.46
	BIC	552.76	546.93	539.46	243.02	241.50	243.03
Switzerland	AIC	256.47	254.29	242.79	189.90	191.87	186.79
	BIC	257.96	257.29	250.10	191.4	194.87	192.83
France	AIC	268.90	270.90	267.74	251.20	253.09	245.70
	BIC	270.39	273.89	275.39	252.70	256.08	252.28
Italy	AIC	285.01	286.78	250.69	189.79	191.62	175.23
	BIC	286.50	289.77	257.59	191.29	194.61	180.78
AUT, CHE	AIC	466.50	465.89	409.65	320.64	322.51	294.40
FRA and ITA	BIC	468.00	468.88	419.14	322.13	325.50	302.29
US	AIC	188.64	182.43	186.33	147.45	148.92	151.33
	BIC	190.13	185.42	192.65	148.95	151.92	156.40

For further international comparison, we consider estimated functions of off-piste and backcountry avalanche fatalities (and off-piste fatalities detached) of Switzerland, France, Italy and the US in Figs. 3–6. In addition, Fig. 7 shows temporal profiles for the combined data summing up the numbers of Austria (AUT), Switzerland (CHE), France (FRA) and Italy (ITA). And for discussion, we are looking at the numbers of Austrian backcountry accidents over time with more than one fatality (Fig. 8).

Finally, the AIC and the BIC of the constant (no trend effect), linear and nonlinear models are reported for model comparison – see Table 2. Lower AIC and BIC values, however, indicate significantly better fits when comparing the different models.

3.2 Regional results

Figures 9 and 10 show the regional distribution of fatal avalanche events (Fig. 9 in total and Fig. 10 off-piste only) using colored maps based on small areas, which are the Austrian municipalities in our case. The coloring, however, is based on Markov random-field estimates of avalanche fatalities as described in the previous Section (deviance explained: total 91.2 %, off-piste 87.1 %); the number corresponding with each spatial unit in the plot is equal to the original count.

In addition to Figs. 9–10, Table 3 gives a list of those municipalities with the most avalanche fatalities in Austria. Further on, we list those avalanche events in Austria with the highest counts of fatalities in Table 4 which turns out to be useful for the discussion section.

Finally, Fig. 11 shows the distribution of alpine terrain ($\geq$ 1500 m a.s.l.) and the distribution of the overnight stays in the winter season 2016 at municipal level (restricted to the 130 municipalities with more than 100 000 overnight stays in Austria) which allows us to discuss possible reasons for the observed distribution of avalanche fatalities in Fig. 9 (Pearson correlation alpine terrain: 0.42; overnight stays: 0.62) and Fig. 10 (alpine terrain: 0.27; overnight stays: 0.66).

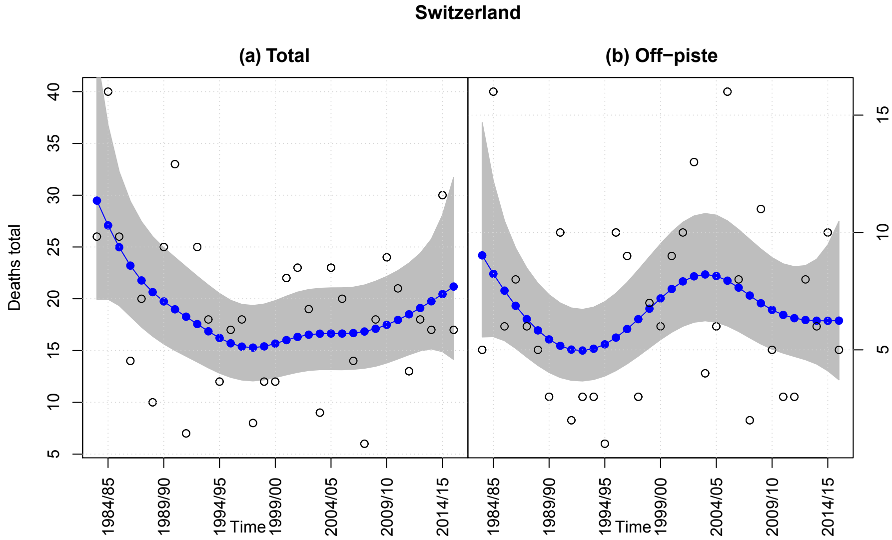

Figure 3. Observed (°) and estimated (•) annual avalanche fatalities – off-piste and backcountry, i.e., total, in **(a)** and off-piste in **(b)** – with 90 % confidence bands (grey) in Switzerland within 1983/1984–2015/2016.

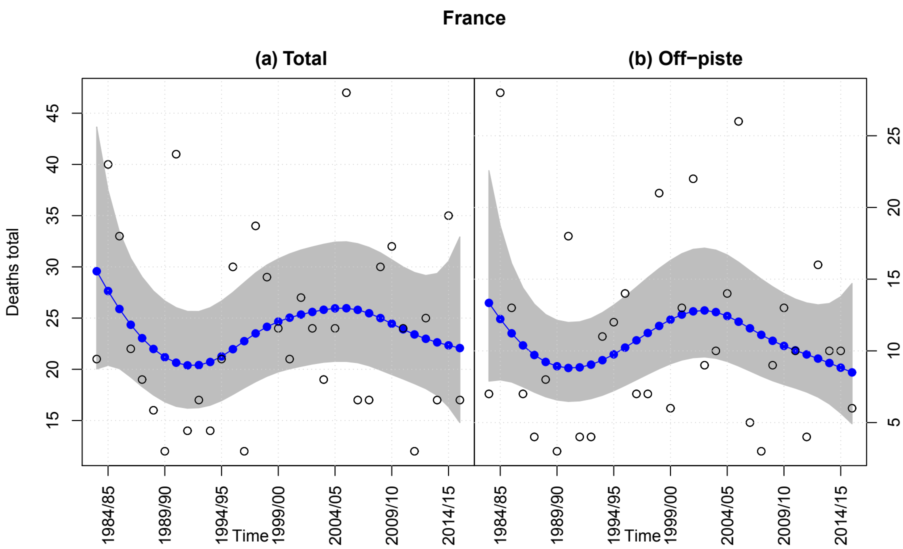

Figure 4. Observed (°) and estimated (•) annual avalanche fatalities – off-piste and backcountry, i.e., total, in **(a)** and off-piste in **(b)** – with 90 % confidence bands (grey) in France within 1983/1984–2015/2016.

4 Discussion

4.1 Temporal analysis with an international overview

If we look at the trend function of Austria in total (see Fig. 1), we notice an increasing trend having its maximum in the winter period 2005/2006 (1969/1970: ca. 12; 2005/2006: ca. 22). In recent years we, however, notice that the number of annual fatalities is slightly decreasing.

Additionally we take notice of a peak in the 1980s ranging between 1981/1982 and 1987/1988. But keeping in mind that increased snowfall has an essential effect on the number of accidents (Harvey, 2008; Harvey et al., 2012; Höller, 2012), increased solid precipitation in the 1980s during wintertime (Laternser and Schneebeli, 2003; Abegg, 1996) could give some evidence for this pattern.

Looking at the off-piste trend function (see Fig. 2), we notice an increasing (linear) trend without any peak in the 1980s. As in the "total" case, the off-piste fatalities are slightly decreasing from the mid-2000s on.

Lower AIC and BIC values (see Table 2) indicate that the nonlinear model is preferable to the constant or linear model – although in the case of "Austria off-piste" the BIC value indicates that the linear model seems to be preferable.

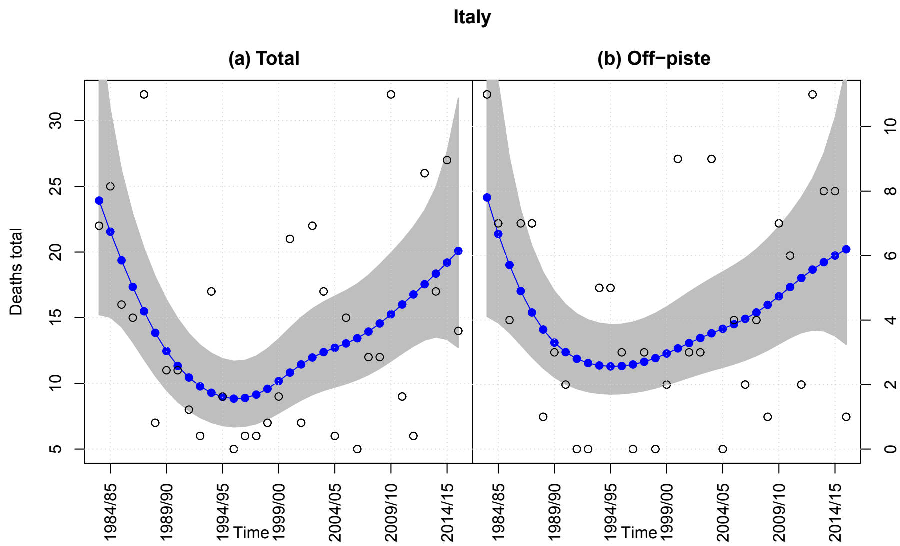

Figure 5. Observed (°) and estimated (•) annual avalanche fatalities – off-piste and backcountry, i.e., total **(a)**, and off-piste **(b)** – with 90 % confidence bands (grey) in Italy within 1983/1984–2015/2016.

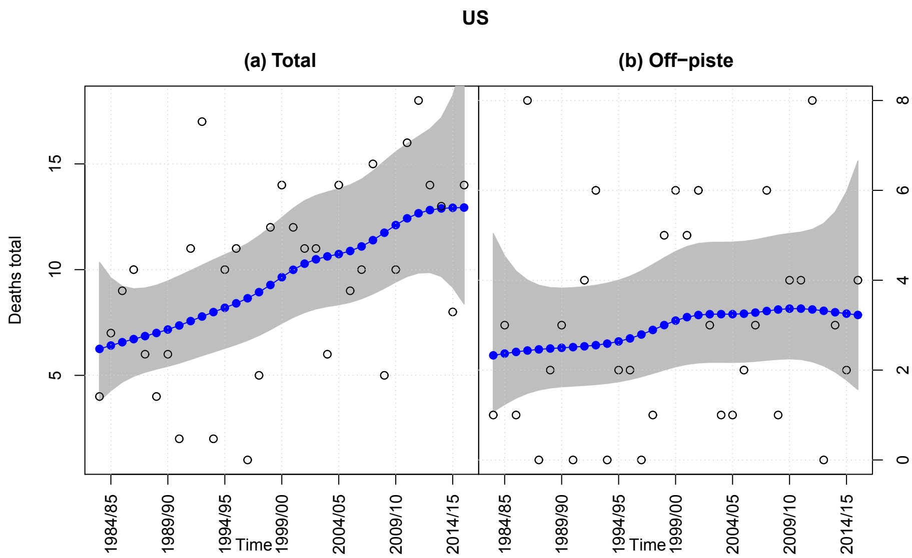

Figure 6. Observed (°) and estimated (•) annual avalanche fatalities – off-piste and backcountry, i.e., total **(a)**, and off-piste **(b)** – with 90 % confidence bands (grey) in the US within 1983/1984–2015/2016.

Considering ARMA effects, we did not find any substantial serial correlation or any sort of periodicity in the remainder x_t. Further on, we notice that there is a lot of variation of the observed counts around estimated function(s).

Comparing Austrian fatal backcountry and off-piste counts within 1983/1984–2015/2016 with results of counts in Switzerland, France, Italy and the US (see Table 1), we notice that, after France (787 fatalities in total, 23.85 fatalities per year), Austria has the second-largest number of total avalanche fatalities (680, 20.61). Having a focus on backcountry fatalities only, Austria is leading (458, 13.88), followed by France (433, 13.12) and Switzerland (395, 11.97). In Austria a share of 32.65 % of total fatalities are due to off-piste accidents (largest value France: 44.98 %; smallest: US: 29.23 %).

Comparisons with total fatality profiles of France, Switzerland and Italy (and profiles of the summing-up of AUT, CHE, FRA and ITA) result in the following:

1. high frequencies in the 1980s,
2. low counts in the 1990s,
3. increasing trend beginning in 2000,

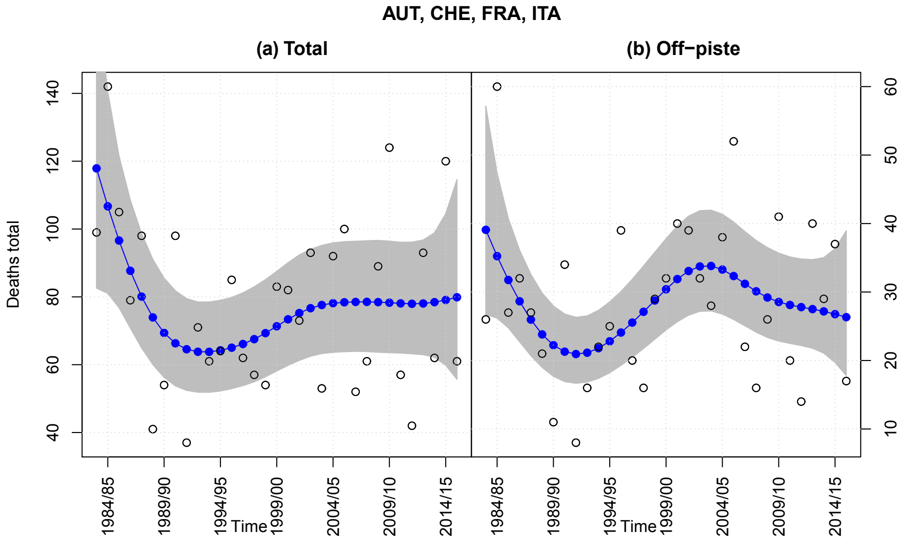

Figure 7. Observed (°) and estimated (•) annual avalanche fatalities – off-piste and backcountry, i.e., total **(a)**, and off-piste **(b)** – with 90 % confidence bands (grey) in AUT, CHE, FRA and ITA (summing-up) within 1983/1984–2015/2016.

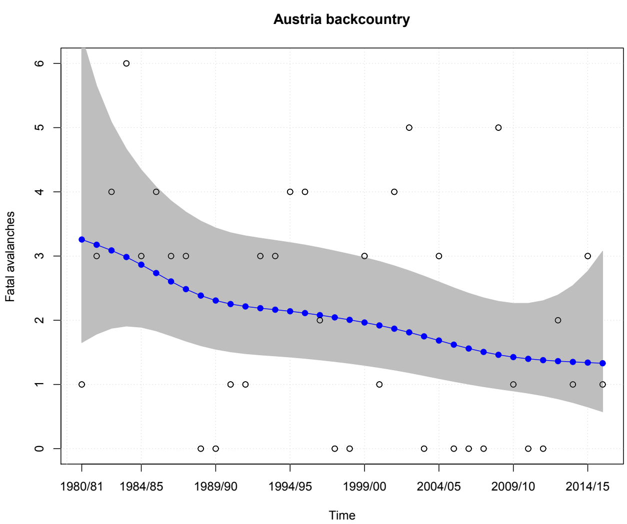

Figure 8. Observed (°) and estimated (•) annual backcountry avalanches (more than one fatality) with 90 % confidence band (grey) in Austria within 1980/1981–2015/2016.

4. to some extent decreasing in recent years,

which in turn is rather similar to the results of Austria.

However, if we consider the results of the US in Fig. 6 (284 total fatalities, 8.61 fatalities per year), we note a positive, almost linear trend without any peaks in the 1980s. The AIC and BIC values indicate that, with the exception of the US (linear model), nonlinear models are preferable (whereas the BIC values of France almost indicate that there is no effect at all in the case of France).

If we compare the off-piste trends of the countries, we notice quite different shapes to those of Austria (positive trend without peak in the 1980s):

1. Switzerland: difference to total trend function, with the peak of off-piste trend around the year 2000 (which is very similar to the profile of the summing-up of AUT, CHE, FRA and ITA);
2. France: decrease of off-piste counts in recent years;
3. Italy: similar to shape as seen in the case of total counts;
4. US: almost no increase; because of the lowest AIC/BIC values, the constant model turns out to be the best one.

Such as in the total case above, lower AIC and BIC values indicate that, with the exception of the US (constant model), nonlinear models are best performing. Usually trend information is given as a linear function in the literature for avalanche data; see, for example, Tschirky et al. (2000), Harvey and Zweifel (2008), Spencer and Ashley (2011) and Page et al. (1999). Our investigations – see AIC and BIC values in Table 2 – showed that (with the exception of the US data) linear models are not appropriate – see also the results of Techel et al. (2016), SLF (2016) and Höller (2017) in the recent research. However, Techel et al. (2016) and Höller (2017) could not find significant results because they were using a nonparmetric test (Mann–Kendall), which is only sensitive to linear or monotonic trend profiles.

At the beginning and the end of the longitudinal profiles we observe larger confidence bands indicating less precise estimates due to missing data in their neighborhoods. As a result of this, extreme estimates at the beginning of the temporal profiles could be less reliable (e.g., in the case of Switzerland total, if we compare the results with those of SLF, 2016).

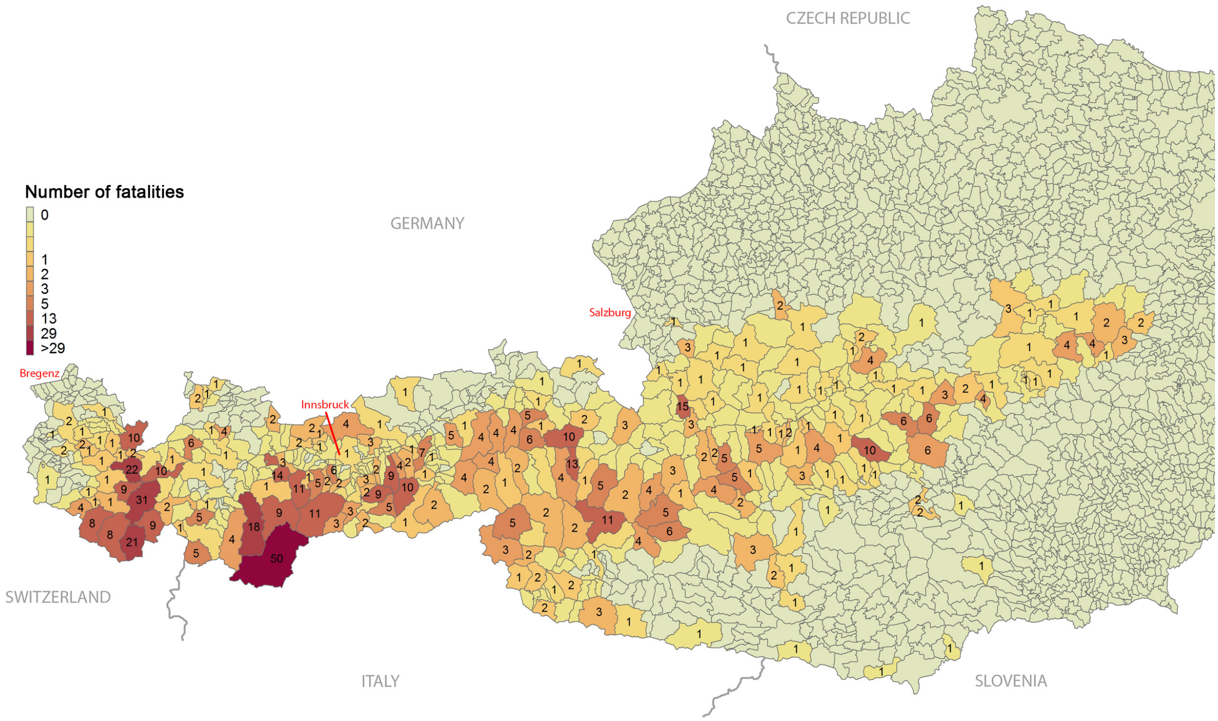

Figure 9. Regional distribution of avalanche fatalities (off-piste and backcountry) in Austria within 1980/1981–2015/2016.

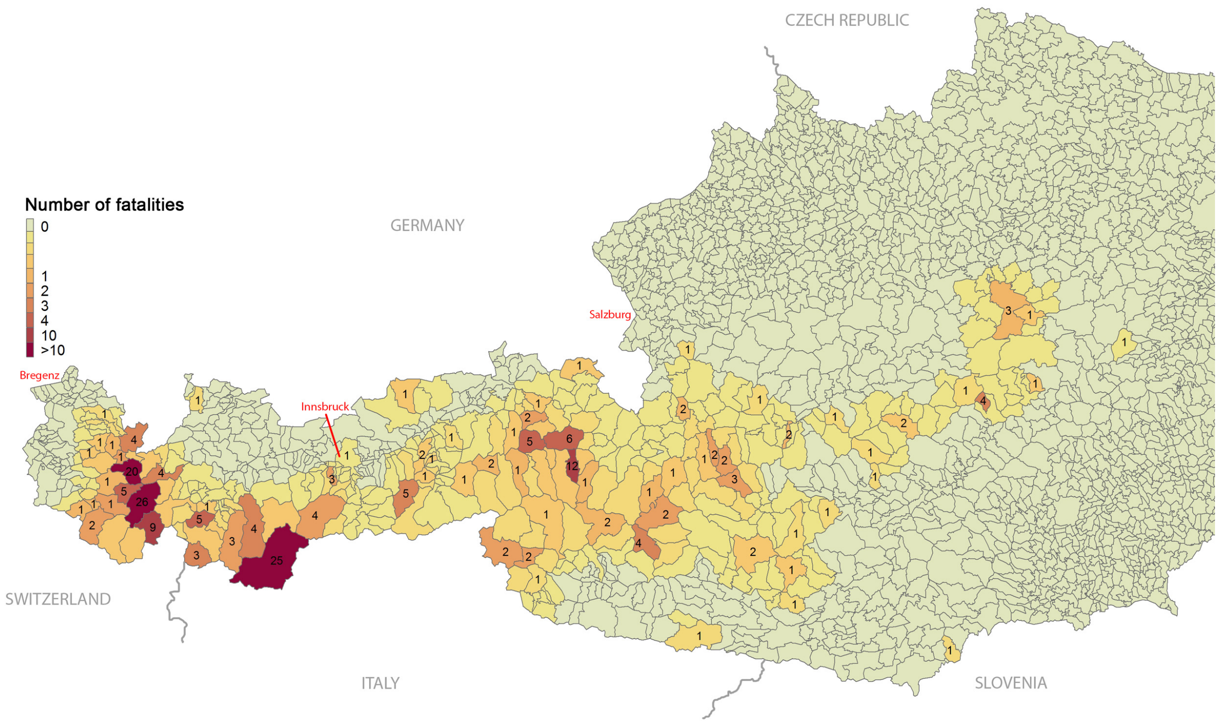

Figure 10. Regional distribution of avalanche fatalities (off-piste) in Austria within 1980/1981–2015/2016.

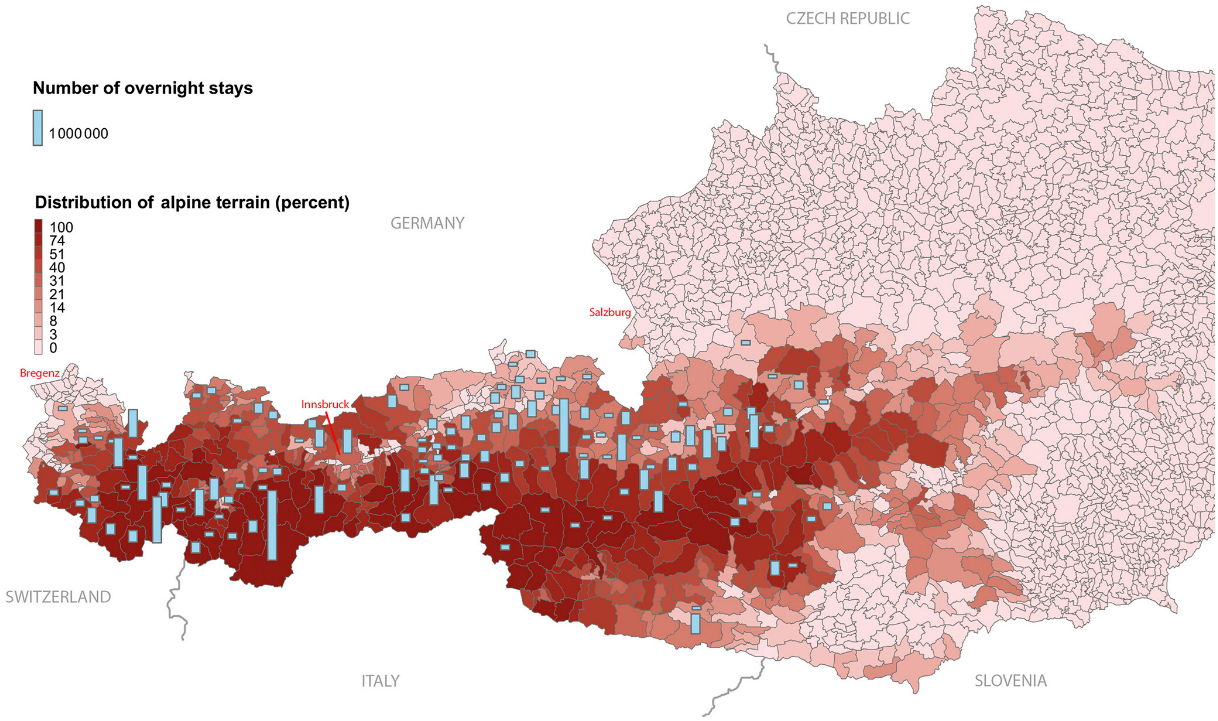

Figure 11. Distribution of alpine terrain (≥ 1500 m a.s.l.) and number of overnight stays in the winter tourist season 2015/2016 at the community level.

We think that single extreme events do not have an influence on the estimated functions because of the robustness of the estimator. In this context, we observe a significant decrease in the number of avalanche fatalities with more than one fatality (see Fig. 8) and AIC/BIC values of the constant (142.77/144.02), linear (139.17/142.37) and nonlinear model (141.19/146.34) suggesting that the linear model is preferable.

The temporal profiles could also be seen as an indicator for low/high-frequency temporal clusters, which are Austria total (six larger values) in the mid-1980s, and Switzerland off-piste, France and Italy total (five smaller values for each) in the early and mid-1990s.

4.2 Regional analysis

In Fig. 9 we explore the regional or spatial distribution of avalanche fatalities in Austria within the years 1981–2016. Here the total area of Austria is divided into small areas, equal to the areas of the Austrian municipalities (211 municipalities with at least one reported fatality). Looking at Table 3, we notice that the municipalities with highest numbers are "Sölden" and "St. Anton a. Arlberg". Around the municipalities St. Anton a. Arlberg and Sölden in the western part of the Austrian federal state Tyrol we observe two clusters or hot spots of increased fatalities:

– the first cluster (CL1), centered around the regions Arlberg and Silvretta, includes the municipalities St. Anton a. Arlberg (number of avalanche fatalities: 31), Kaisers (10), Klösterle (9) and Lech (22) in Arlberg, and the municipalities St. Gallenkirch (8), Gaschurn (8), Galtür (21) and Ischgl (9) in Silvretta;

– the second cluster (CL2) – located in the southern part of Ötztal, Kühtai and Stubai – includes the municipalities Sölden (50), St. Leonhard i. Pitztal (18) and Längenfeld (9) in the Ötztal Alps, and the municipalities St. Sigmund i. Sellrain (11), Silz (14), Sellrain (5) and Neustift i. Stubaital (11) in Kühtai-Stubai.

Further on, we observe some smaller spots in the federal states:

– Tyrol (Tuxer Alpen): Navis (9), Wattenberg (9), Schmirn (5) and Tux (10);

– Salzburg (Saalbach): Saalbach-Hinterglemm (10) and Niedernsill (13);

– Styria (Triebener Tauern – Seckauer Tauern): Gaal (6), Wald am Schoberpaß (6) and Hohentauern (6).

Finally we notice some single areas with increased frequency, such as Mittelberg Vorarlberg (10), Heiligenblut Carinthia (11), Werfenweng Salzburg (15) and Pusterwald Styria (10). Some single areas with increased frequencies,

Table 3. Number of avalanche fatalities (off-piste, backcountry and total) in Austria within 1980/1981–2015/2016 stratified for communities with more than four fatalities in the observation period.

Community	Backcountry	Off-piste	Total
Sölden	25	25	50
St. Anton am Arlberg	5	26	31
Lech	2	20	22
Galtür	21	0	21
St. Leonhard im Pitztal	14	4	18
Werfenweng	13	2	15
Silz	14	0	14
Niedernsill	1	12	13
Neustift im Stubaital	7	4	11
Heiligenblut am Großglockner	9	2	11
St. Sigmund im Sellrain	11	0	11
Tux	5	5	10
Kaisers	6	4	10
Mittelberg	6	4	10
Saalbach-Hinterglemm	4	6	10
Pusterwald	9	1	10
Klösterle	4	5	9
Navis	9	0	9
Ischgl	0	9	9
Längenfeld	9	0	9
Wattenberg	9	0	9
Gaschurn	8	0	8
St. Gallenkirch	6	2	8
Fügenberg	5	2	7
Jochberg	1	5	6
Axams	3	3	6
Gaal	6	0	6
Häselgehr	6	0	6
Wald am Schoberpaß	6	0	6
Hohentauern	4	2	6
Mallnitz	6	0	6
Prägraten am Großvenediger	5	0	5
Tweng	2	3	5
Nauders	2	3	5
Kitzbühel	3	2	5
Serfaus	0	5	5
Sellrain	5	0	5
Schmirn	5	0	5
Fusch an der Großglocknerstraße	5	0	5
Alpbach	4	1	5
Bad Gastein	3	2	5
Rohrmoos-Untertal	5	0	5
Untertauern	3	2	5

such as Werfenweng (15) and Niedernsill (13), are due to disastrous single avalanche events; see, for example, Table 4.

Figure 10 plots the distribution of the off-piste fatalities (without backcountry fatalities; 77 municipalities with at least one reported off-piste fatality). As a conclusion we notice two hot spots of off-piste fatalities, which are St. Anton a. Arlberg–Lech–Ischgl (Arlberg, Ischgl) and Sölden (southern part of Ötztal).

Furthermore, there are some single spots or small clusters, such as Tux Tyrol (5), Jochberg Tyrol (5), Saalbach-Hinterglemm Salzburg (6) and Niedernsill Salzburg (12).

If we compare Fig. 9 and Fig. 10 (or if we have a look at Table 3), we notice centers of off-piste avalanche fatalities in CL1 such as Lech (20 off-piste fatalities out of 22 total, 90.91 % off-piste), St. Anton a. Arberg (26 out of 31 total, 83.87 %) and Ischgl (9 out of 9 total, 100 %), while the accidents of Galtür (0 % off-piste), St. Gallenkirch (25 % off-piste) and Gaschurn (0 % off-piste) are mainly due to backcountry skiers.

Looking at CL2, the fatal accidents of our interest are mainly caused by backcountry skiers, except for Sölden, where the off-piste rate is about 50 % (25 out of 50 total, $\geq$ 32.65 % in the case of Austria).

Figure 11 (distribution of alpine terrain and overnight stays in the winter season 2015/2016) tries to give some idea in order to explain the spatial distribution of avalanche fatalities of Figs. 9 and 10. Obviously, the percentage of alpine terrain at municipal level coincides with the number of fatalities. However, there are alpine areas with lower numbers of fatalities than in those in the western part of Tyrol; see, for example, East Tyrol. The majority of fatalities are restricted to two clusters, which is more or less only a small part of the terrain of our interest.

Looking at the overnight stays in Fig. 11, we notice that the largest counts of overnight stays coincide with the largest counts of total and off-piste fatalities (Sölden, St. Anton a. Arlberg, Lech), but there are winter tourist regions with lower numbers of avalanche fatalities; see, for example, the Tauern region or the northeastern part of Tyrol. In the case of the total number of fatalities, overnight stays are partly misleading because, for example, they do not take into account the considerable number of native backcountry skiers around Innsbruck.

This is more or less in agreement with considering the size of Austrian ski resorts, see Fleischhacker (2016), instead of overnight stays. Spencer and Ashley (2011) stated that areas with higher winter sports activity are those with higher number of avalanche fatalities.

Finally, if we consider the spatial patterns of buildings exposed to snow avalanches in Austria (Fuchs et al., 2015), we could find some remarkable congruences (looking at CL1 and CL2) when comparing them with avalanche fatalities at municipal level.

5 Conclusions

As a result of the trend analysis we notice an increasing trend (although decreasing in recent years) of off-piste and backcountry avalanche fatalities within the winter periods 1967/1968–2015/2016. This clearly contradicts the widespread opinion that the number of fatalities is constant over time.

Comparing results of off-piste and backcountry avalanche fatalities in Austria with other relevant countries, we notice the second-highest number of off-piste and backcountry fa-

Table 4. List of avalanche events (off-piste or backcountry) in Austria within 1980/1981–2015/2016 with more than two fatalities in each event.

Date	Location	Municip.	Fatalities
31 Jan 1982	Werfenweng	Werfenweng	13
28 Mar 2000	Schmiedinger Kogel	Niedernsill	12
28 Dez 1999	Jamtalhütte – Gde. Galtür	Galtür	9
5 Apr 1987	Idalpe	Ischgl	6
28 Mar 1988	Jamtal	Galtür	6
2 May 2009	Schalfkogel	Sölden	6
6 Feb 2016	Wattener Lizum	Wattenberg	5
21 Mar 1985	Sonntagkarzinken, Schladm. Tauern	Rohrmoos-Untertal	4
14 Feb 1988	Hühnereggen, Stubaier Alpen	Sellrain	4
12 Apr 1993	Querkogeljoch, Ötztaler Alpen	Sölden	4
18 Feb 1997	Luxnacher Sattel	Häselgehr	4
22 Jan 2005	Rendl	St. Anton a. Arlberg	4
1 Mar 1981	Hohe Veitsch	Mürzsteg	3
19 Feb 1984	Hoher Gleirsch, Karwendelgebirge	Scharnitz	3
4 May 1985	Speikogel, Kitzbüheler Alpen	Westendorf	3
8 Jan 1986	Kühkarkopf, Hohe Tauern	Fusch a. d. Großglocknerstr.	3
1 Apr 1986	Tschambreuspitze, Silvretta	Gaschurn	3
7 Apr 1986	Windachscharte, Stubaier Alpen	Sölden	3
21 Dez 1986	Lattenberg Triebener Tauern	Wald a. Schoberpaß	3
6 Jan 1987	Fluchtalpe, Kleines Walsertal	Mittelberg	3
18 Apr 1987	Scharkogel	Uttendorf	3
21 Dez 1991	Scharnitzfeld, Wölzer Tauern	Pusterwald	3
3 Jan 1995	Schöngraben/Törli	St. Anton a. Arlberg	3
11 Feb 1995	Scheibenspitze	Navis	3
9 Mar 1996	Frommerkogel, Tennengebirge	Hüttau	3
3 Apr 1996	Murkarspitze, Gde. Längenfeld	Längenfeld	3
16 Mar 2000	Wasserradkopf	Heiligenblut	3
19 Nov 2000	Roßkarschneid	Sölden	3
30 Jan 2003	Scharnitzalm, Scharnitzfeld	Pusterwald	3
20 Dez 2004	Mohnenfluh	Lech	3
22 Feb 2005	Sulzkogel	Silz	3
5 Mar 2005	Rotschrofenspitze	Kaisers	3
18 Jan 2013	Mittagskofel, Karnische Alpen	Lesachtal	3

talities in Austria and the largest number of backcountry fatalities in Austria. We notice similar estimated functions if we compare Austrian results with results of the relevant European countries. However, the off-piste trend function of Austria is quite different to those of the other relevant European countries (but similar to those of the US).

As a result of the regional analysis we notice two hot spots of avalanche fatalities in Fig. 9: St. Anton a. Arlberg (31) (Arlberg–Silvretta) and Sölden (50) (southern part of Ötztal, Stubai–Kühtai).

Because of the increasing trend (although decreasing in recent years) and the rather "narrow" regional distribution of the fatalities, initiatives aimed at preventing avalanche accidents are highly recommended, for instance starting a "campaign against avalanche accidents" in the centers of the clusters St. Anton and Sölden. This should especially be done in order to prevent the large number of off-piste (freerider) fatalities in St. Anton–Lech–Ischgl and Sölden. Additionally, we observe decreasing numbers of fatal backcountry avalanches with more than one fatality (see Fig. 8), which could be the effect of more awareness of danger in the last 30 years.

Unfortunately, we are not able to verify the influence of increased numbers of backcountry and off-piste skiers over time because there is no valid information about frequencies of backcountry and off-piste skiers in general. However, we find some evidence that increased winter overnight stays (which could be seen as an evidence for increased winter sports activity) has an effect on higher number avalanche fatalities; see Fig. 11.

Finally, we do not hesitate to mention that further research is needed, for example to explore the influence of new fallen snow, temperature etc. on the number of fatalities in a spatiotemporal model. For this purpose, further and more precise data are necessary.

Data availability. Data sets used in this article are availaible from the correspondence author upon request.

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