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Using tree-ring signals and numerical model to identify the snow avalanche tracks in Kastamonu, Turkey

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Abstract Many parts of our planet are exposed to natural disasters such as snow avalanches, floods and earthquakes. Detailed knowledge on these natural disasters is crucial for human safety. On December 25–26, 1992, two avalanches occurred at Kayaarkası-Kastamonu in northern Turkey. The first avalanche took place at night of 25–26 December and caused no damage. The second avalanche took place at morning of 26 December, killed four people and did damage to properties. The purpose of the present study is to determine the effects of the snow avalanches on tree rings and to investigate the boundaries and velocities of the avalanches using a numerical simulation model and the tree-ring data. Increment cores from 71 trees in the avalanche-impacted area and the control site were sampled to obtain individual standard chronologies. In the analyses, trees were grouped as (1) heavily damaged by the avalanche, showing a decrease in tree-ring widths since the event, (2) trees heavily damaged by the avalanche, showing an increase in tree-ring widths a couple of years later the event and (3) trees that were not damaged by the avalanche. In this study, one of the most important results is the precise determination of the temporal and spatial patterns of the undocumented avalanche (the first avalanche) event. Avalanches were numerically simulated using dynamical avalanche simulation software ELBA+. Comparison of the simulation model with tree-ring analysis revealed valuable results about the boundaries of the zone of influence of the avalanches.

Keywords Tree rings · Snow avalanche · Dendrochronology · *Abies bornmuelleriana* · Kastamonu · Turkey

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1 Introduction

Snow avalanches are a common natural hazard in most mountainous regions of the planet. Avalanches generally occur in high and steep mountain slopes, where rapid, gravity-driven masses of snow move downhill (Mears 1992; McClung and Schaerer 1993; Görcelioğlu 2003). Avalanches sometimes contain rocks, soil and/or ice (McClung and Schaerer 1993; Weir 2002) as well as stems and branches (Hübl et al. 2002; Quinn and Philips 2000). The size of an avalanche is a function of the volume and type of the snowpack, slope, aspect, temperature, elevation, wind direction and topography (concavity of the slope) (Quinn and Philips 2000). Avalanches can start from any slope types such as channeled and unconfined, except where dense forest is present and is able to prevent an avalanche from starting (McClung and Schaerer 1993; Tremper 2001; Maggioni and Gruber 2003). Avalanches rarely release on slopes <25° and slopes with an angle >60° (McClung and Schaerer 1993). On slopes with angles smaller than 25°, the component of gravity forces along the slope is not strong enough to initiate an avalanche and on slopes with an angle >60°, avalanches are very frequent and of small dimension, since big, lasting deposition is not possible (McClung and Schaerer 1993; Maggioni and Gruber 2003).

To predict avalanche runout zones, numerical models have been used for decades. Currently AVAL-1D (Christen et al. 2002) and RAMMS (Christen et al. 2008) (developed by the SLF Institute in Switzerland), ELBA+ (NiT 2005) (developed by NiT GmbH, Austria) and SAMOS (Sampl and Zwinger 2004) (developed by Austrian Forest Service) are widely used in Europe. ELBA+ is a 2D simulation model especially developed for dense flow avalanches. The software has been calibrated on approximately 150 avalanches (Volk and Kleemayr 1999). ELBA+ has generally been used for hazard mapping, protection works and design purposes (Sauermoser and Illmer 2002).

Trees can record avalanche events during their lifetime in their tree-ring archives. Using dendrochronological methods, it is possible to date snow avalanche events (Burrows and Burrows 1976; Schroder 1978; Carrara 1979; Hansen-Bristow and Birkeland 1980; Bryant et al. 1989; Jenkins and Hebertson 1994; Schweingruber 1996). Dendrochronological data and vegetation structure can be utilized to determine frequencies, boundaries and accumulation zones of avalanches in the areas lacking information on the avalanches. However, vegetation analysis is a general approach and could not give exact dates of the avalanches. Only a few dendrochronological studies were performed on the snow avalanches (Schönenberger 1975, 1978, 1981; Burrows and Burrows 1976; Shroder and Butler 1987; Butler 1979, 1985; Butler and Malanson 1985; Carrara 1979; Hull and Scott 1982; Johnson et al. 1985; Potter 1969; Schweingruber 1996; Smith et al. 1994; Muntan et al. 2005; Ives et al. 2002; Casteller et al. 2007, 2008).

In Turkey, snow avalanches are serious problems in the high mountainous regions. A total of 365 people were injured, and 1,325 (yearly average 23.7) people were killed by the avalanches between the years 1951–2007 (GDDA 2009). In the first half of 1990s, many snow avalanches occurred; 328 people were killed during the winter of 1991–1992, and 135 during 1992–1993. In the west Black Sea Region, 13 people were killed in three snow avalanches during the winter of 1992–1993 (Gürer and Yavaş 1994). The studies on the snow avalanches are generally related with the avalanches resulting with deaths. The snow avalanches we study in this article occurred in Topçular Village (Küre-Kastamonu) during the night of December 25–26, 1992, and on the morning of December 26, 1992, which killed four people. The purpose of the present study is to determine the effects of the snow avalanches on tree rings and to investigate their boundaries and velocities by modeling and comparing with tree-ring analysis.

2 Materials and methods

2.1 Site description

We studied two avalanche tracks in the study area (33°39′20″E, 41°54′40″N). The avalanche tracks are located on the steep slopes on the upper part of Kayaarkası district of Topçular Village (Küre-Kastamonu; Fig. 1). The average slope of the avalanche tracks is 30.5°, aspect is south-southwest and mean altitude is 750 m a.s.l. The rockfall activity is also common in this area. Total annual precipitation (1930–2000) and mean annual temperature (1930–2000) of Kastamonu meteorological station, which is the closest to the study area (69 km horizontal distance), are 464 mm and 9.7°C, respectively (Fig. 2). The main tree species in the area is *Abies bornmuelleriana* Mattf. However, *Quercus* sp., *Carpinus betulus* L. *Ostrya carpinifolia* Scop. and *Populus alba* L. represent with solitaire or small groups. They are young, and most of them grew after the year of 1992.

The two snow avalanches occurred in different tracks: the first was during the night of December 25–26, 1992, and the second was on the morning of December 26, 1992, and four people died in the second one. Because the second avalanche caused deaths, some information about this avalanche was recorded by General Directorate of Disaster Affairs, and the event is well remembered by the villagers. On the contrary, the first avalanche did not cause any damage, and there are virtually no official records about that avalanche. After dendrochronological analysis, we recognized that another avalanche could have occurred in the sampled area. This idea was also confirmed by the villagers, but they could not locate the exact place of this avalanche. The type of both avalanches was slab avalanche (Erenbilge 2008).

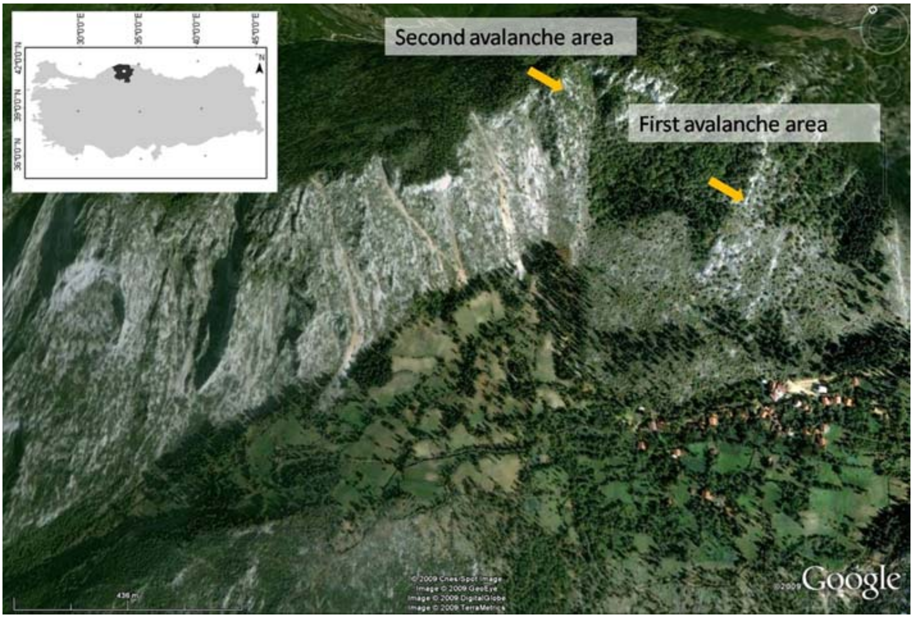

Fig. 1 The two avalanche tracks. The first avalanche occurred at night of December 25–26, 1992, and the second one on the morning of December 26, 1992. Image source: Google Earth

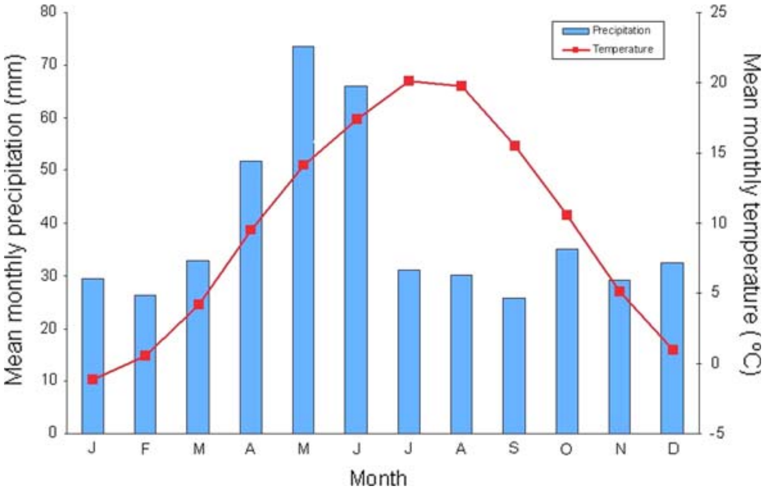

Fig. 2 Mean monthly precipitation (1930–2000) and mean monthly temperature (1930–2000) of Kastamonu meteorological station

2.2 Sampling

Only *Abies bornmuelleriana* trees grow within the avalanche track. Testimonials by the villagers and the stumps observed in the field indicate that some trees died and were cut down during the recent years. All trees in the avalanche tracks and the runout zones were sampled, and the increment cores from 61 trees were extracted. Two increment cores were taken from up and downslope of each tree to identify compression wood in avalanche-impacted trees. Ten more trees from a control area were also sampled for comparison. The coordinates of the sampled trees were noted in the field. In addition, some visual morphological features of the sampled trees were noted.

2.3 Tree-ring analysis

Samples were fine-sanded and cross-dated using standard dendrochronological techniques (Stokes and Smiley 1968). The width of each annual ring on the cores and cross-sections was measured with the precision to the nearest 0.01 mm using the LINTAB-TSAP Measuring System (RinnTech, Germany). From 61 sampled trees, 49 trees (98 cores) from the avalanche tracks and 10 trees (20 cores) from control site could be measured. The program COFECHA was used to test the accuracy of raw measurements (Holmes 1983; Grissino-Mayer 2001). Each ring width series was standardized by means of a negative exponential or linear regression to remove trends related to age, size and the effects of stand dynamics (Fritts 1976; Cook et al. 1990a), so individual standard chronologies of each tree from the avalanche areas were obtained. To build a master chronology for control site, the individual indices of 10 control trees were combined into a single averaged chronology using a bi-weight robust estimate of the mean (Cook et al. 1990b). These analyses were performed using ARSTAN program (Cook 1985; Grissino-Mayer et al. 1996).

2.4 Dating of the events

In each cross-dated sample, we assessed the following features (Casteller et al. 2007): (1) the years of the reaction wood onset and the number of years with reaction wood (see e.g., Carrara 1979; Smith et al. 1994), (2) the years with presence of scars (exposed or hidden by the bark) or various other damage (see e.g., Mears 1975; Johnson 1987) and with traumatic resin canals (see e.g., Cherubini et al. 1997), (3) the years in which abrupt growth changes (suppressions-releases) occurred (Butler 1985).

The collected samples were divided into three groups based on abrupt growth changes after the snow avalanche occurred in 1992. The three groups were constructed using 49 trees:

- Group 1. Trees heavily damaged by the avalanche, showing a decrease in tree-ring widths since the event. Some trees in this group died.
- Group 2. Trees heavily damaged by the avalanche, showing an increase in tree-ring widths a couple of years after the event.
- Group 3. Trees that were not damaged by the avalanche.

We also calculated abrupt growth changes for each group and for the control site with IMPACT software (Grissino-Mayer et al. 1997), which uses tree-ring measurement series to compare mean growth before and after a disturbance (e.g., Casteller et al. 2008). We selected a time span starting 14 years before the avalanche and ending 14 years later. In order to identify changes in radial growth, we compared mean growth variation of each group with the control site.

After building individual chronologies, three groups and one control site chronologies were constructed. These chronologies were compared visually. Principle Component Analyses (PCA; Reyment and Jöreskog 1993) were performed for Group1 and Group 2. Growth patterns of each group were graphed by drawing PC1 (Principle Component 1).

2.5 Mapping

All sampled trees are indicated on the map based on their groupings. The control site is also indicated on the map.

The boundaries of the known (second) avalanche occurred in the morning of December 26, 1992 were determined (1) using a GPS instrument (2) with help of the villagers who witnessed the avalanche and also (3) based on the records of the Public Works and Settlement Directorate of Kastamonu. Regarding the magnitude and the boundaries of the first avalanche occurred during the night of December 25–26, 1992, no exact official information exists. Therefore, this avalanche was mapped and simulated based exclusively on dendrochronological results and field observations.

2.6 Numerical avalanche simulations

Avalanche velocity and flow height were analyzed by using 2D avalanche simulation model ELBA+. This is a raster-based numerical simulation model for dense snow avalanches. ELBA+ implements a modified version of the Voellmy model for the friction calculation. The main modification compared to the original model by Voellmy is that the turbulent friction parameter ξ varies in time and space. For the dynamic calculation of ξ, a logarithmic law based on a modified form of the Colebrook–White equation was applied. Variable friction parameters are calculated for each location at each time step (NiT 2005).

$$a = g \cdot \left(\sin\psi - sign(v) \cdot \left(\mu \cdot \cos\psi + \frac{v^2}{\xi \cdot h} \right) \right) \quad (1)$$

$$\xi = 8 \cdot g \cdot \left(-2 \cdot \log_{10}\left(\frac{k_s}{12 \cdot h} \right) \right)^2 \quad (2)$$

where a acceleration of the avalanche [m/s^2], g gravitation [m/s^2], ψ slope angle [°], v velocity [m/s], μ dry friction parameter [], h flow height [m], ξ dynamic friction parameter [m s^{-2}] and ks roughness length [m].

The integration of Eq. 2 replaces the expert estimation of ξ, which has a significant influence on the calculation results, by two physically interpretable variables: the flow height and the roughness length. Back-calculations of well-observed avalanches showed that parameter ks could be kept constant for the standard case (avalanche on snow cover). This means that the user only has to estimate the release area and the release height for avalanche calculations. ELBA+ has also a simple snow entrainment model allowing the avalanche body to entrain snow when a certain local normal stress is exceeded.

Recently, the friction model was extended by a variable flow regime. This approach assumes Mohr–Coulomb friction in the starting zone. In the track, the friction shifts to a Voellmy fluid. In the runout zone, again Mohr-Coulomb friction is assumed. The transition between the friction models is governed by the local flow velocity.

ELBA+ is integrated into ESRI ArcGIS 9.0. ELBA+ manages all relevant data within a spatial database, allowing analyzing avalanche simulation data in time and space. Key features are multiple parameterization, easy data display, and animation creation and automated reporting. ELBA+ was implemented in the Microsoft Net environment (NiT 2005).

Required input files for ELBA+ are (1) a triangulated irregular network (TIN) data, (2) release area characteristics, (3) friction parameters as well as (4) a geo-referenced map, aerial photo or satellite image to overlay on the TIN. The simulations with ELBA+ were based on digitizing 1:25,000 scaled topographical map and field surveying data using total station device. Release area characteristics (size and location) were determined with discussing villagers as eyewitnesses and interpretation of aerial photo.

The area and mean altitude values used for the release area of the first avalanche were 4,411 m^2 and 842 m a.s.l. (ranging from 836 m to 907 m), respectively; the values used for the release area of the second avalanche were 12,575 m^2 and 848 m a.s.l. (ranging from 803 m to 893 m), respectively. The friction parameters μ and ξ were chosen by trial and error method. Consequently, 0.38 μ and 1,000 ξ values were chosen, which shows best fit for the events used in simulations. Snow height for both release areas was chosen as 1.40 m, as written in official report.

Model results were compared with the results of dendrochronological analysis to find the boundaries of the avalanches.

3 Results and discussion

3.1 Dendrochronological results

The most visible result was an abrupt change (suppression) in the tree-ring widths the year after the event. Reaction wood formation was rare, and no traumatic resin canal formations in years after the event were observed. Trees grouped upon the severity of the damage

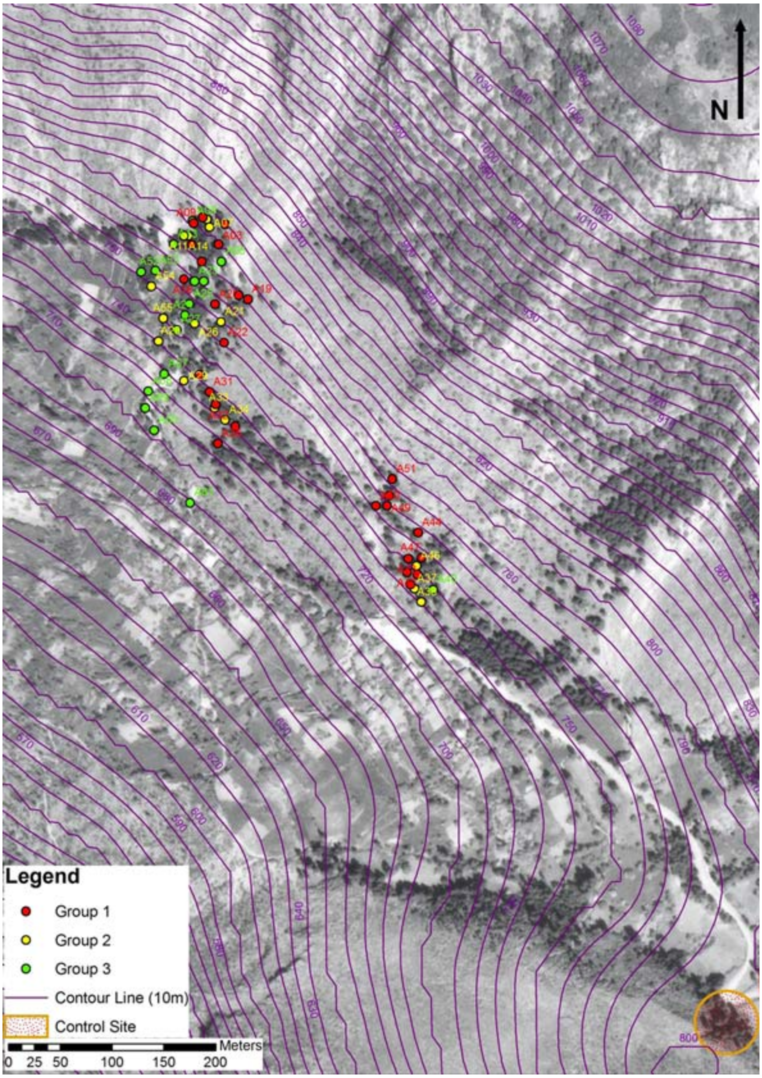

Fig. 3 Trees sampled and their groups overlapped on an aerial photograph. The grouping was made based on the intensity of the growth changes after the 1992 avalanche event. The control site is indicated with a *brown circle*

caused by the avalanches are indicated in Fig. 3 in red (Group 1), yellow (Group 2) and green (Group 3-not damaged). Of the 49 trees, 24 trees fell into Group 1, 14 trees into Group 2 and the remaining 11 fell into Group 3. As a result, 38 trees were damaged and the 11 remaining ones were not damaged by the avalanches. The distribution of the trees and control site was mapped (Fig. 3).

A marked growth decrease can clearly be seen since year 1993 in the Group 1. The similar changes during the next 2–3 years after the avalanche can also be seen in Group 2. Tree-ring widths in trees of this group restarted to increase 2–3 years after the event

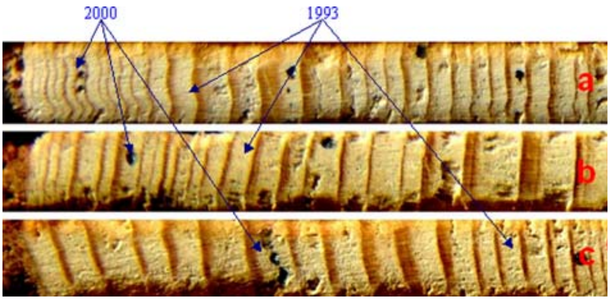

Fig. 4 Ring width variations representative of the trees from the three different groups: **a** Group 1, **b** Group 2 and **c** Group 3. The year of 1993 is the first year after the avalanche event

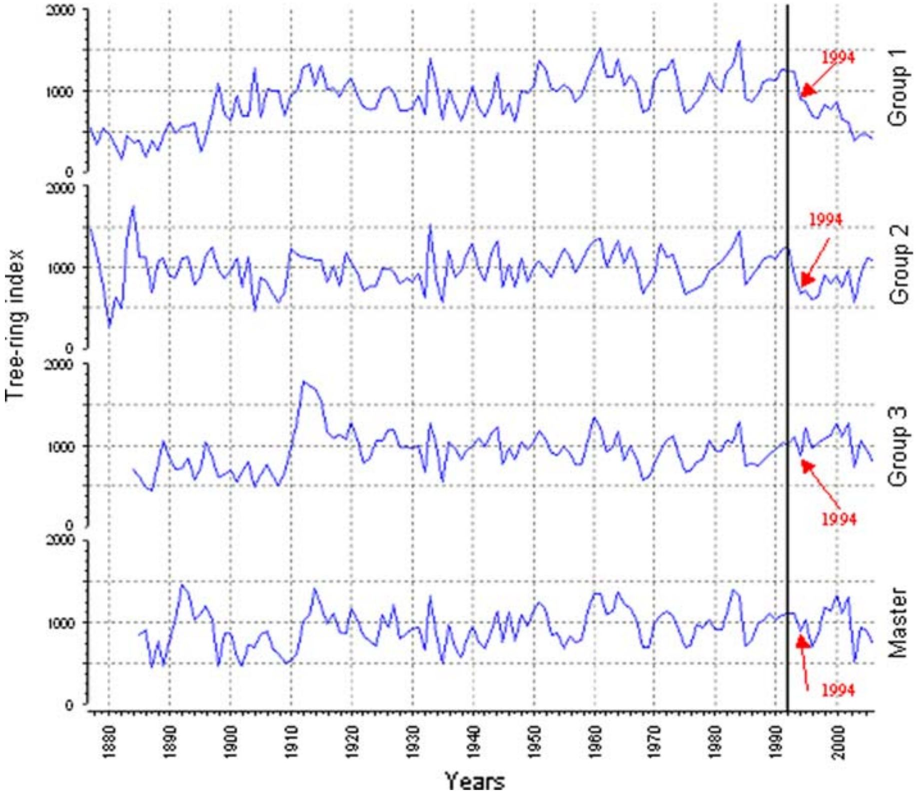

Fig. 5 The site chronologies of the groups of the collected samples and the master chronology from the control site. The vertical line corresponds to year 1992. The year of 1994 was an extremely dry year for the region

(Fig. 4). The trees in the Group 3 revealed a similar growth pattern as the one observed in the trees from control site (Fig. 5).

We compared the changes in radial growth of trees in each group and control site in time spans starting 14 years before and ending 14 years after the event (Table 1). The

Table 1 Changes in radial growth of trees in each group and control site

	Mean growth before the event year	Mean growth after the event year	Growth variation after the event year (%)*
Group 1	11.25	5.63	50.06
Group 2	9.43	6.03	63.93
Group 3	9.23	8.54	92.64
Control	10.54	9.08	86.14

The calculations were done with the program IMPACT using time spans starting 14 years before and ending 14 years after the event

* Mean growth before the event year is taken as 100, growth variation after the event year is equal to % of mean growth before

variations in tree-ring widths in control area and the Group 3 were similar (86.14 and 92.64%, respectively), and no important variation before and after 1992 was found. On the contrary, an important variation in growth was found in Group 2 (63.93%) and especially in Group 1 (50.06%).

Some trees showed branch flagging (Fig. 6); the lower branches of the trees on the avalanche path were broken down, and probably the thin roots of trees were also broken down. All these effects can cause an abrupt decrease in tree-ring widths. The year of 1994, the second growing year after the avalanche, was an extremely dry year for the region (Akkemik et al. 2005, 2008; Griggs et al. 2007; Köse 2007). The cambial activity in the heavily damaged trees (Group 1 and 2) could have decreased considerably during and after

Fig. 6 Tree from the avalanche track showing branch flagging

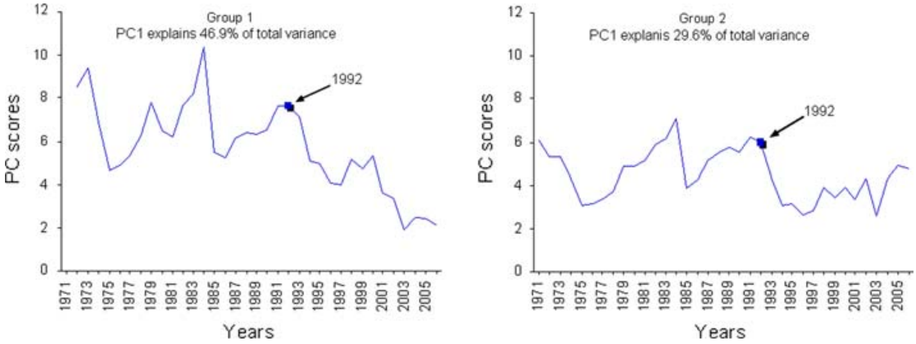

Fig. 7 PCA results of the affected groups (Group 1 and Group 2)

1994 due to both the avalanche event and the drought, resulting in narrow tree rings (Figs. 4, 5). In the following years just after the avalanches, some trees died and were cut down. The stems remaining from these trees can be seen in the field. Because of improved light conditions, tree-ring widths in some of the trees restarted to increase a couple of years after the avalanche (Group 2, Figs. 4, 5).

According to the PCA results, PC1 of the Group 1 explains 46.9% of the total variance, whereas the PC1 of the Group 2 explains 29.6% of the total variance (Fig. 7).

According to the official records and the testimonies provided by local people, no avalanche events occurred at the study site besides the one of from 1992. This is confirmed by the similarity in ring-width patterns between the trees in avalanche zone and in the control zone previously to 1992. A small number of resin ducts were observed but those corresponded to different years and therefore probably not part of a common signal.

3.2 Mapping and determining of the tracks of the avalanches

3.2.1 The avalanche occurred at night of December 25–26, 1992 (the first avalanche)

After mapping all the sampled trees (Fig. 3), it was determined that some of the trees affected by the avalanche are located outside of the known avalanche track. This led us to think that another avalanche event occurred during the same year in the neighboring area. After discussing with the villagers again, they confirmed that another avalanche occurred at night of December 25–26, 1992. The villagers could only give the approximate location of this avalanche, called as "first avalanche" here.

Trees located in this first avalanche track produced very similar tree-ring patterns with the known avalanche track (referred to as the second one in this paper). The trees of Group 1 in both avalanche tracks were graphed separately in Fig. 8. The response of the trees after events is very similar. As a result, based on the dendrochronological analysis, information from villagers, topography of the area and investigation of aerial photo, the release area of the first avalanche was determined, and the avalanche was numerically simulated. Simulation results are as follows (Figs. 9, 10):

The length of the avalanche track: 360 m
Max velocity: 16.79 m/s (in 105th m)
Max pressure: 67.68 kPa (in 105th m)
Max flow height of the avalanche: 0.84 m (in 40th m)

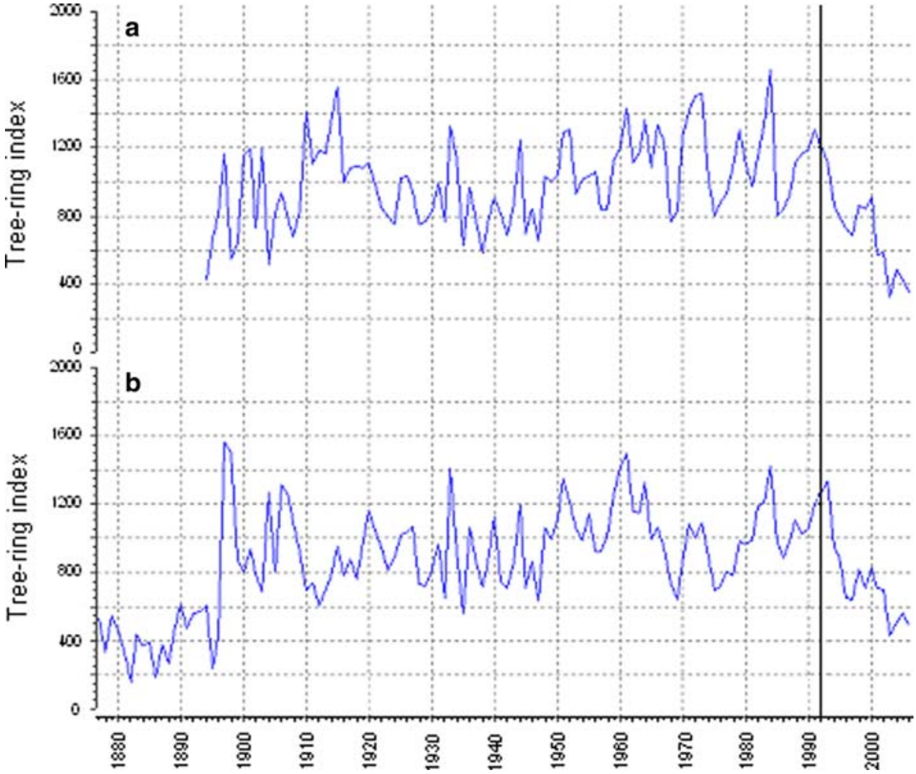

Fig. 8 The graphs of the heavily damaged trees (Group 1). *a* Group 1 of the first avalanche area, *b* Group 1 of the second avalanche area. The responses of the trees in these two avalanche areas are similar. The *vertical line* corresponds to year 1992

3.2.2 The avalanche occurred in the morning of December 26, 1992 (the second avalanche)

This avalanche was recorded officially and was more severe than the first one. It killed four people in the village, who lived on the lower part of the area. The avalanche simulation results are as follows (Figs. 9, 11):

The length of the avalanche track:	840 m
Max velocity:	24.3 m/s (in 250th m)
Max pressure:	141.82 kPa (in 250th m)
Max flow height of the avalanche:	5.08 m (in 320th m)

3.2.3 Combining the simulations and tree-ring results

The presence of abrupt growth changes is a common feature in *Abies bornmulleriana* trees affected by snow avalanches, principally in those trees located in the track and borders areas (e.g., Casteller et al. 2007, 2008). As stated by Casteller et al. (2007), cross-dating of the samples from avalanche-killed trees provides precise dates of avalanche occurrences.

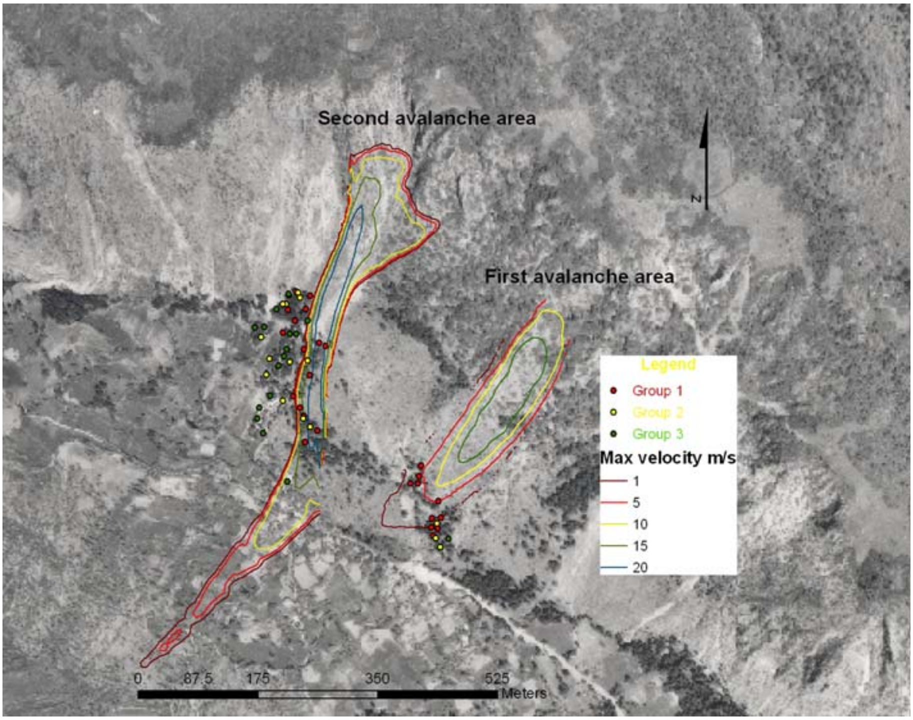

Fig. 9 Comparison between the simulated avalanche events and the spatial patterns reconstructed using dendrochronological methods. Group 1 (*red*) and 2 (*yellow*) represent trees affected by the avalanches, and Group 3 (*green*) represents non-affected trees. A very good similarity can clearly be seen in the results of both methods. The affected trees are inside the avalanche areas. In the west border of the second avalanche, unaffected trees can clearly be seen

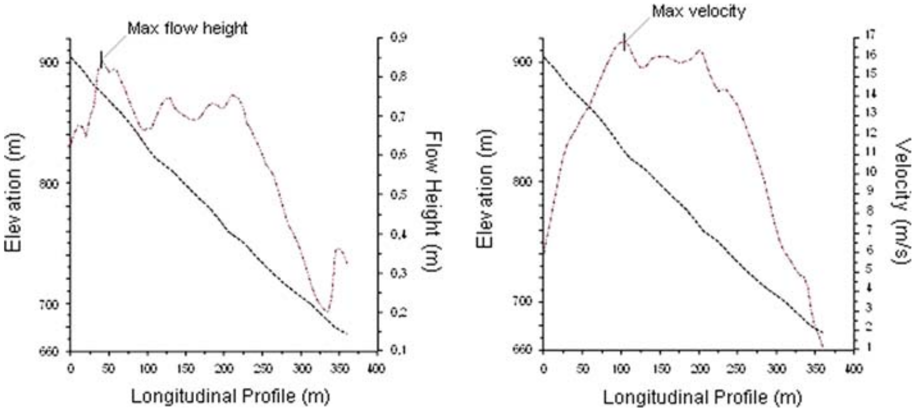

Fig. 10 Max flow height and max velocity of the first avalanche occurred at night of December 25–26, 1992

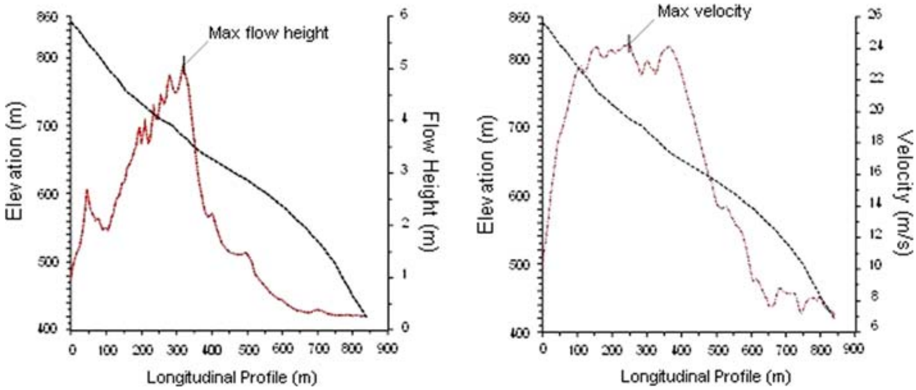

Fig. 11 Max flow height and max velocity of the second avalanche occurred on the morning of December 26, 1992

In this study, the avalanche-killed trees fell into the Group 1 and revealed precise information on the avalanches (Fig. 9).

In both avalanche tracks, simulation results are compatible with dendrochronological results. At the first avalanche track, many of the damaged trees are located at the runout zone of the avalanche. In this area, the small number of damaged trees identified stay at the outside but very close to the simulated avalanche border. In the second avalanche area, the damaged trees largely remain on the avalanche track determined by the simulation model. Some of damaged trees at the upper part of the avalanche track have remained outside of the simulated avalanche border. Dendrochronological results showed that the border of the avalanche could be wider than that of the simulation model.

The exact boundaries of the avalanche tracks could not be determined using tree-ring data because the sampled trees do not cover the whole avalanche area. However, the part of the area with trees revealed reliable results.

4 Conclusions

The trees located on the snow avalanche tracks revealed valuable information about past events in our study areas. Some of the living trees have visible damages such as broken and adventitious branches, branchless part on the upside of the stems, partly dead crowns. Together with these visible damages, we determined that the most important effect of the snow avalanches were the abrupt decrease in tree-ring widths. In this study, one of the most important results is the precise determination of the temporal and spatial patterns of the undocumented avalanche event. Comparing the simulation models and tree-ring data, we located the boundaries of the avalanches to a satisfactory extent.

Based on the results of the simulations and dendrochronological analysis, we can conclude that simulation models and tree-ring data should be combined to locate the exact boundaries and tracks of avalanches in the region.

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