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Can we discriminate snow avalanches from other disturbances using the spatial patterns of tree-ring response? Case studies from the Presidential Range, White Mountains, New Hampshire, United States

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ABSTRACT

Dendrogeomorphology has been recognized as a useful tool to reconstruct past snow avalanche chronologies, especially in remote areas where archives are non-existent. In recent years, there have been a multiplicity of snow avalanche studies based on tree-ring analysis. Yet, the dendrogeomorphic procedure applied to snow avalanches still lacks consensus within the scientific community. This paper illustrates four issues regarding this method encountered on a dataset encompassing 293 trees sampled from 4 sites in the White Mountains (New Hampshire, United States). (1) Separating a sample in an upslope and downslope subgroup allowed to reconstruct a more thorough avalanche chronology. (2) On the other hand, a strong response at a site sheltered from any avalanche track was attributed to extreme snow loadings with a return period well above 100 years. (3) In addition to climatic disturbances, ecological disturbances such as windthrows can cause an anatomical response in the trees similar to snow avalanches. An avalanche track might act as a wind tunnel, making the underlying runout zone a suitable site to windfalls. Sampling in transects can assist in determining the limit between avalanche-related and wind-related disturbances. (4) Early-spring torrential floods and avalanche activities at a multi-process site exhibit distinct spatial patterns in the dendrogeomorphological response that allow discrimination between the two processes in the reconstruction of past chronologies. While the dendrogeomorphologist should be cautious of these issues, their acknowledgement is an opportunity to understand the interactions between the different ecological, climatic and geomorphological processes operating on the forested slopes in the alpine–subalpine environment.

1. Introduction

The term dendrogeomorphology was defined by Alestalo (1971) as "*the analysis of growth reactions of trees affected by geomorphological processes by dendrochronological methods*". Since then, tree-ring analysis has become an accepted technique applied to several geomorphic and geological phenomena (cf. Solomina, 2002; Stoffel et al., 2010; Speer, 2015). The approach is based on datable disruptions in the ring pattern that occur: (i) when the environment surrounding a tree changes or, (ii) when the tree is damaged, i.e., scarring, broken branches, foliage loss, or tilting. In recent years, there has been an increasing number of studies on snow avalanches using tree-ring analysis to reconstruct years of avalanche activity (e.g., Boucher et al., 2003; Muntan et al., 2004; Casteller et al., 2007; Laxton and Smith, 2009; Garavaglia and Pelfini, 2011), to identify the weather scenarios responsible for the triggering of regional snow avalanche activity (e.g., Dubé et al., 2004; Germain et al., 2009; Muntan et al., 2009; Casteller et al., 2011), to calibrate avalanche models (e.g., Casteller et al., 2008; Eckert et al., 2013; Schläppy et al., 2014) or to analyze the impact of ecological and anthropogenic disturbances on snow avalanche regimes (e.g., Germain et al., 2005). Since the pioneer works in dendrogeomorphology (Potter, 1969; Mears, 1975; Burrows and Burrows, 1976; Shroder, 1978, 1980; Butler, 1979; Carrara, 1979), it has been recognized as a useful tool to provide a better understanding of snow avalanches, particularly in regions where historical documentation is lacking, and to characterize the relative hazard degree in moun-

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tainous environments for risk determination and mapping (Salm, 1997; Lerner-Lam, 2007).

There have been many recent studies (e.g., Heinrich et al., 2007; Butler and Sawyer, 2008; Germain et al., 2010; Corona et al., 2012; Stoffel et al., 2013; Chiroiu et al., 2015) concerning tree-ring analysis methodology applied to snow avalanches, but consensus is still lacking. Indeed, the accuracy of this methodology has yet to be examined (Luckman, 2010), particularly in regard to other forces, such as soil creep, snow creep, and wind, which may contribute to observable impacts on tree rings. With this in mind, and considering the methodological and statistical developments in dendroclimatology as well as our understanding of spatiotemporal sensitivity and the non-stationary responses of trees to climate (i.e., Briffa et al., 1998; Loehle, 2009; Leonelli et al., 2011; Housset et al., 2015), it is surprising that many of these issues with dendrogeomorphology are still poorly documented. The fact that dendrogeomorphology is now a sub-discipline of tree-ring analysis, but with its own original methods of investigation (Stoffel et al., 2013), may partially explain this methodological weakness, considering that the only studies which compared tree-ring inferred avalanche activity with historical archives only succeeded in reconstructing ≤40% of avalanche years (Butler and Malanson, 1985; Reardon et al., 2008; Kogelning-Mayer et al., 2011; Corona et al., 2012; Schläpply et al., 2013). Indeed, small avalanches might not have a sufficiently long runout or the destructive capacity to be recorded by trees. As for higher magnitude events, they can destroy earlier evidences of avalanche activity (Germain et al., 2009).

Some authors warn us about the validity of avalanche chronologies in sites affected by other geomorphic (e.g., torrential floods, debris flows, etc.), ecological (e.g., windthrows, epidemics, fires, etc.,) or climatic (e.g., ice storms, snow loading, etc.) disturbances (e.g., Stoffel et al., 2013). There is however a lack of data-based evidence to support the fact that the dendrochronological responses of these different disturbances can be discriminated from the snow avalanche signal in the tree rings. Dendrochronology has been recognized as a useful tool for avalanche risk assessment in areas where no historical archives exist on the occurrence and extension of past snow avalanches. Moreover, many of these avalanche paths are also affected by other disturbances. In that regard, there is a need to explore the possibilities of discriminating different disturbances from snow avalanches in tree-ring series. A method to differentiate tree-ring signals induced by avalanches from those by debris flow was developed using the position of the reaction within a tree-ring (Stoffel et al., 2006). The authors inferred that if the reaction is located in the dormant wood or the early-earlywood, the response was caused by a snow avalanche, whereas responses located in later during the growth season were attributed to debris flow. However, this time and resource-consuming method is limited in the discrimination of disturbances co-occurring during the dormant season. For example, a late-spring snow avalanche or torrential floods related to the melting of snow could both occur before or at the very beginning of the growth season.

The aim of this paper is to test whether it is possible to isolate the dendrochronological signal caused by snow avalanches from other disturbances in different avalanche paths of the White Mountains (New Hampshire, United States). First, in a forested environment where the runout zone is not clearly defined and where it can be located on slopes >10°, collecting samples to the extreme limit of the runout zone can give precious information about the spatial extension of major avalanches. However, most methods in the literature on tree-ring data applied to snow avalanches use a threshold of impacted trees above which one can infer avalanche activity for a given year. Collecting samples until the extreme limit of the runout zone can dilute results from smaller avalanches in the noise of the growth disturbance (GD) time-series. Therefore, even a sampling network covering the entire runout may not allow to develop a representative chronology of avalanche events. We thus test whether we could build a more complete chronology by treating different subsamples in a same path affected by an extreme avalanche. Second, the 1969 winter, where the extreme snowfalls correspond to a 325-year return period, provides an opportunity to compare the signal from extreme snow loading to the disturbance in snow avalanche couloirs. Third, a windthrow next to a closed forest that was disturbed by a snow avalanche in 1969 allows the evaluation of the difference in the tree-ring response. This is especially relevant in a mountain environment such as Mount Washington, where the strong winds have an important ecological impact on the forested slopes. Finally, we question whether spatial patterns of tree-ring response can lead to the discrimination of avalanche-related dendrochronological signal from torrential floods occurring in early spring. Indeed, major floods occurred statewide in 1987 and 2007 springs; these events were likely to have caused torrential erosion in mountain environments. At a larger scale, since 1951, in New England, the months of March, April and May exhibit the highest annual flood relative frequency following either rainstorms, rain-on-snow or a combination of rainstorms and snowmelt (Collins et al., 2014).

2. Regional setting

This study was carried out on different avalanche paths in the Presidential Range of the White Mountains (New Hampshire, United States, 44°16′ N 71°18′ W, Fig. 1). The highest summit, Mount Washington (1917 m a.s.l.), is located in the Presidential Range, a North to South oriented ridge of 2748 ha above treeline. Most avalanche paths in the range are located in Pleistocene glacial cirques all around this alpine ridge and extend into the subalpine red spruce-balsam fir forest. As a result of the intense winter activity by backcountry skiers and alpine climbers, and of the spatial variability of avalanche regimes (Joosen 2008), a micro-scale forecasting by the United States Forest Service (USFS) Snow Rangers has provided daily avalanche conditions for the different avalanche paths in the two most visited cirques since the winter of 1959. However, the avalanche database only begins in 2006 and there is no record of activity prior to that date. A retired USFS snow ranger recalls the unique avalanche activity of the 1969 winter, during which important snowfalls (1.394 cm on Mount Washington summit) caused extreme runouts in many avalanche paths of the Presidential Range.

The average winter temperature (December–April) on the summit of Mount Washington is −11.8 °C. The precipitation from November to April falls primarily as snow, with an annual amount of 714.2 cm. Mount Washington is known for its extreme winds, with monthly recorded peak gusts above 200 km/h for every month. In winter, the summit station records hurricane strength gusts (119 km/h) on average for two days out of three (Gordon, 1989). Due to snow drifting, there is frequently high avalanche danger associated with a 5–7 cm snowfall and high winds (Joosen, 2008). In 1987 and 2007, heavy rain in April associated with snowmelts caused statewide floods in New Hampshire (Fontaine, 1987; Flynn, 2008). During both of these events, peak discharges equalled or exceeded the 100-year recurrence interval at stream gages close to Mount Washington. This study presents tree-ring chronologies from four sites on the eastern side of Mount Washington (Fig. 1). The physiographic characteristics of each site are presented in Table 1.

2.1. Hillman's Highway (HH)

Hillman's Highway (HH) is a confined avalanche track comprising two different starting zones. Because they are located downhill from a large alpine plateau, they are prone to accumulate snow